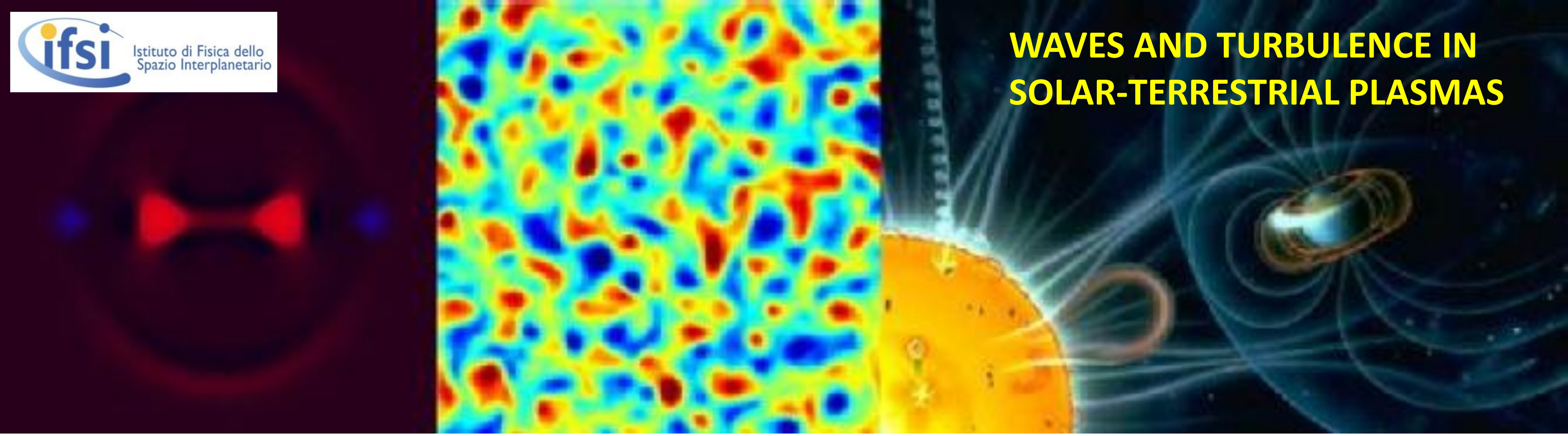

Turbulence in the Solar Wind: an Overview

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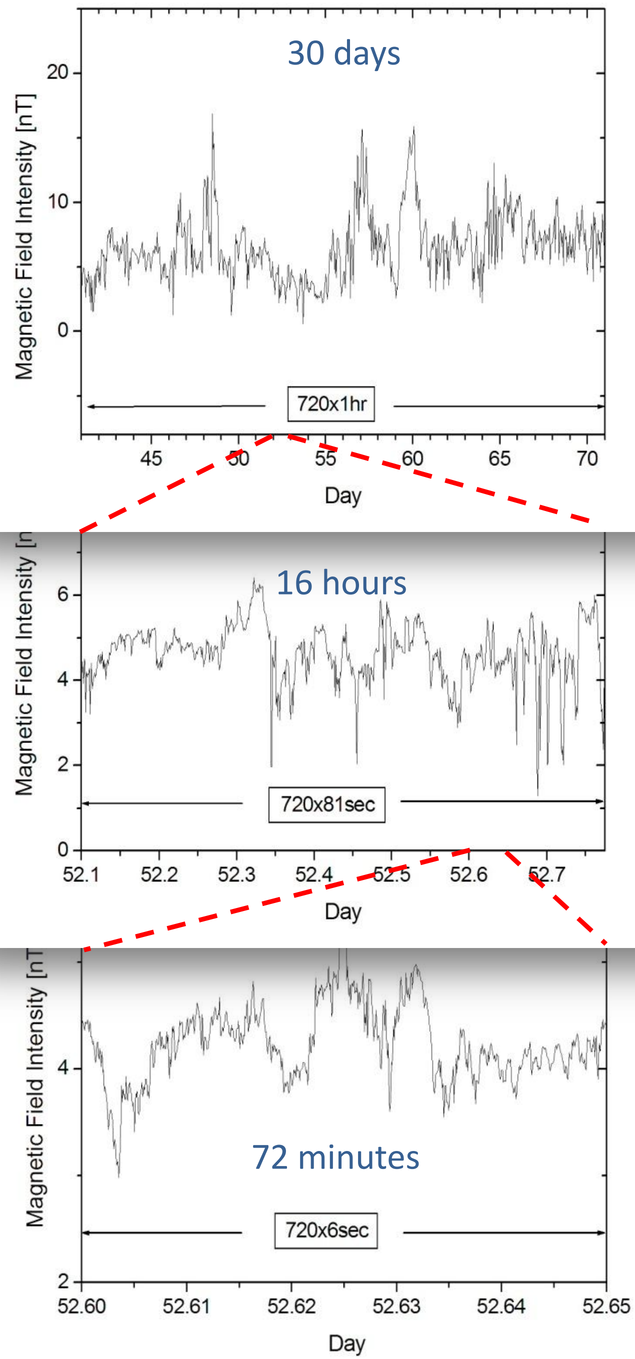
3) Liquid Crystal Laboratory, INFM-CNR, Rende, Italy.

RAS Lecture Theatre, Burlington House,
Piccadilly, London, 12 March 2010

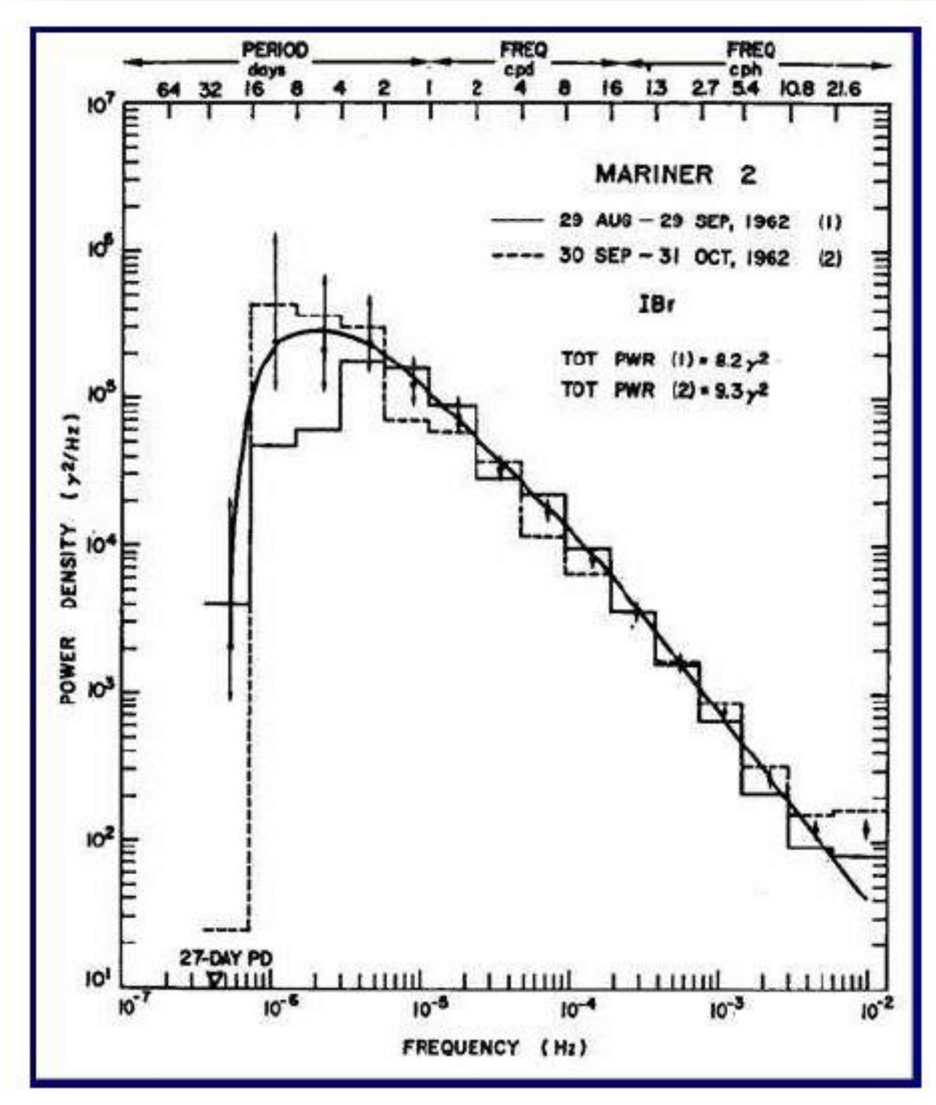


Interplanetary fluctuations show self-similarity properties

$$v(\lambda) = \mu(r)v(r\lambda)$$

The solution of this relation is a power law:

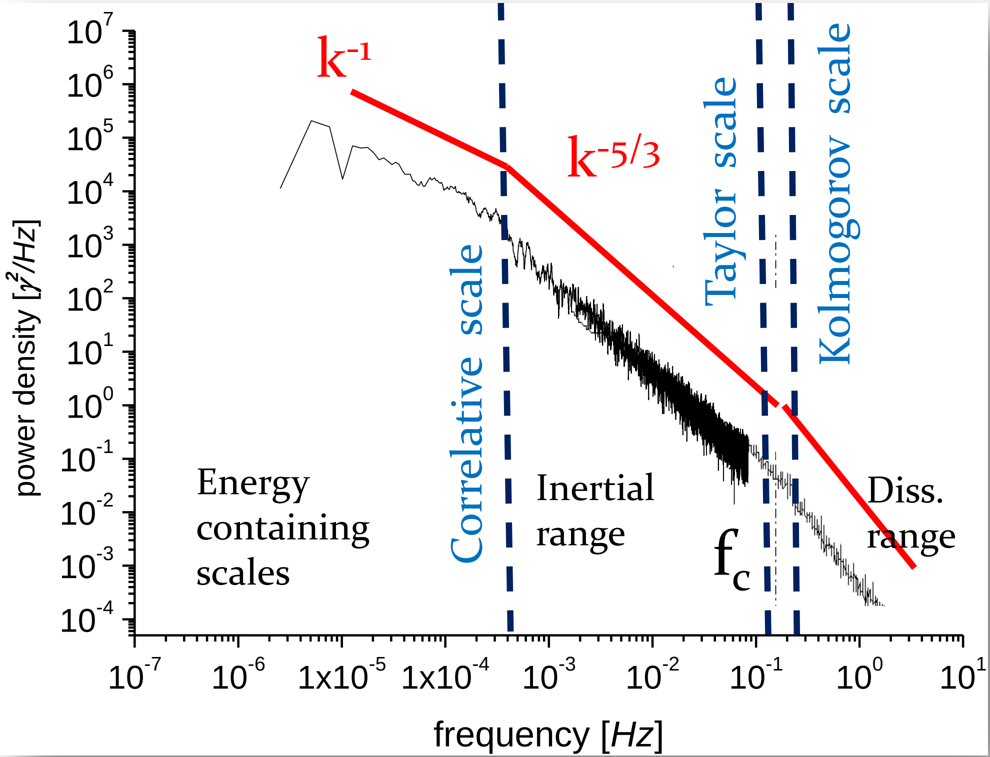
$$v(\lambda) = C\lambda^h$$



First magnetic energy spectrum (Coleman, 1968)

The first evidence of the existence of a power law in solar wind fluctuations

Characteristic scales in turbulence spectrum



typical IMF power spectrum in at 1 AU

[Low frequency from Bruno et al., 1985, high freq. tail from Leamon et al, 1999]

- Correlative Scale/Integral Scale:
  - the largest separation distance over which eddies are still correlated. i.e. the largest turb. eddy size.
- Taylor scale:
  - The scale size at which viscous dissipation begins to affect the eddies.
  - Several times larger than Kolmogorov scale
  - it marks the transition from the inertial range to the dissipation range.
- Kolmogorov scale:
  - The scale size that characterizes the smallest dissipation-scale eddies

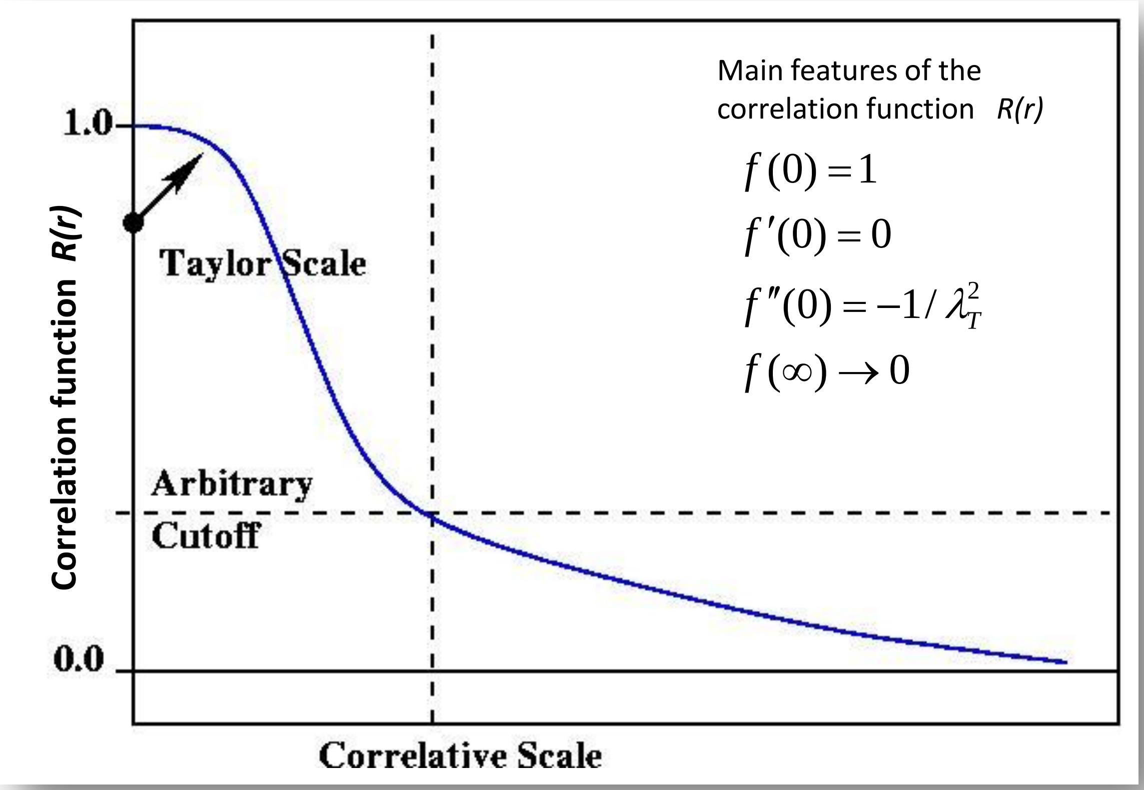
$$R_m = \left(\frac{\lambda_C}{\lambda_T}\right)^2$$

(Batchelor, 1970)

The *Taylor Scale* and *Correlative Scale* can be obtained from the two point correlation function

$$R(r) = \langle V(x+r)V(x) \rangle_x / \langle (V(x))^2 \rangle$$

- Taylor scale:
  - Radius of curvature of the Correlation function at the origin.
- Correlative/Integral scale:
  - Scale at which turbulent fluctuation are no longer correlated.



(adapted from Weygand et al., 2007)

We can determine:

- the *Taylor Scale* from Taylor expansion of the two point correlation function for $r \rightarrow 0$:

$$R(r) \approx 1 - \frac{r^2}{2\lambda_T^{\ 2}} + \ldots$$

(Tennekes, and Lumley , 1972)

where *r* is the spacecraft separation and *R(r)* is the auto-correlation function.

- the *Correlative Scale* from:

$$R(r) = R_0 \exp\left(-r / \lambda_C\right)$$

(Batchelor, 1970)

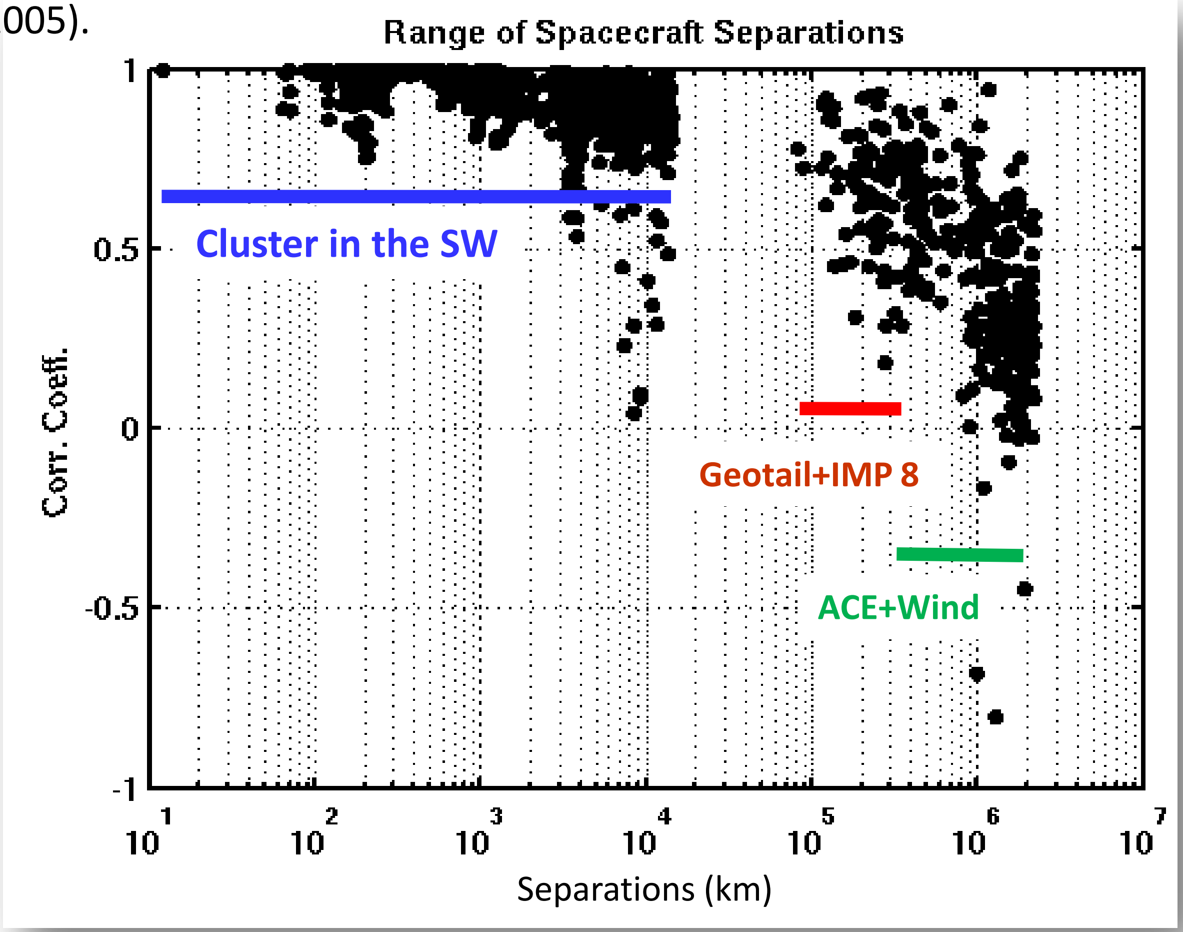
- the magnetic Reynolds number from:

$$R_m = \left(\frac{\lambda_C}{\lambda_T}\right)^2$$

(Batchelor, 1970)

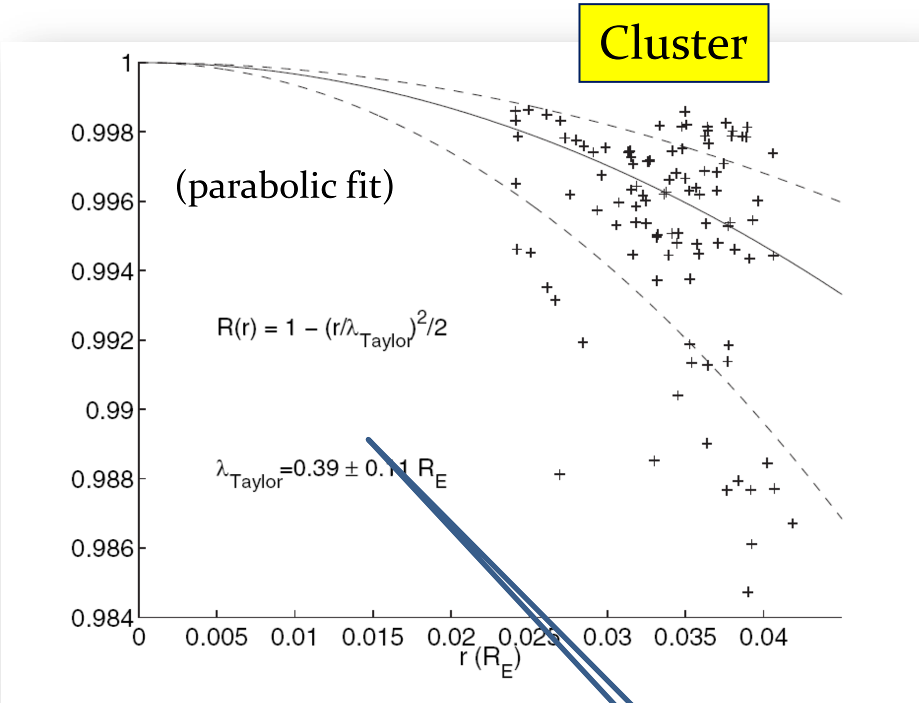
•First experimental estimate of the Reynold’s number in the solar wind (previous estimates obtained only from single spacecraft observations using theTaylor hypothesis)

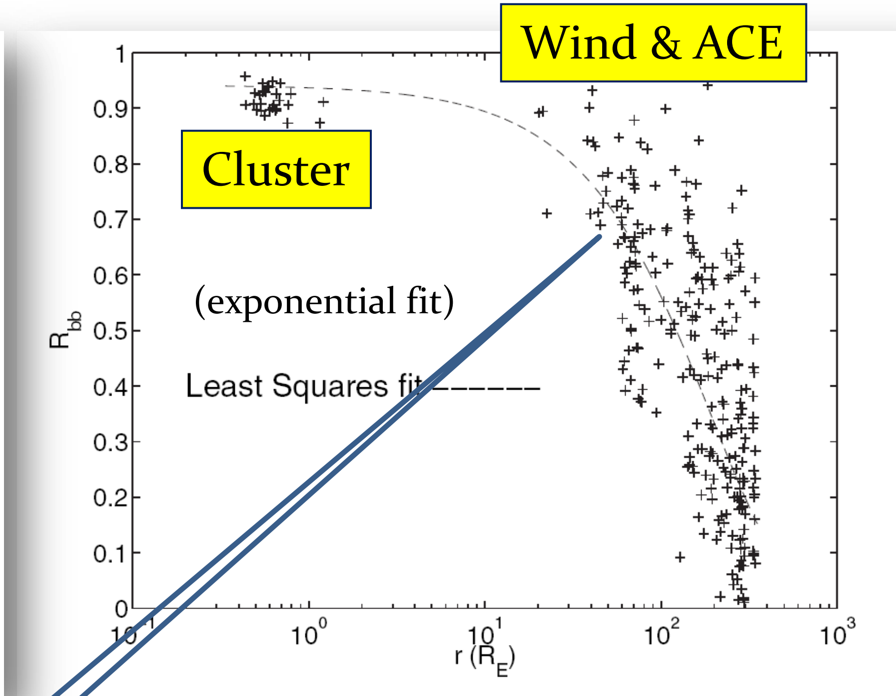
•First evaluation the two-point correlation functions using simultaneous measurements from Wind, ACE, Geotail, IMP8 and Cluster spacecraft (Matthaeus et al., 2005).



(Matthaeus et al., 2005, Weygand et al., 2007)

Experimental evaluation of λ_C and λ_T in the solar wind at 1 AU





(Matthaeus et al., 2005
Weygand et al., 2007)

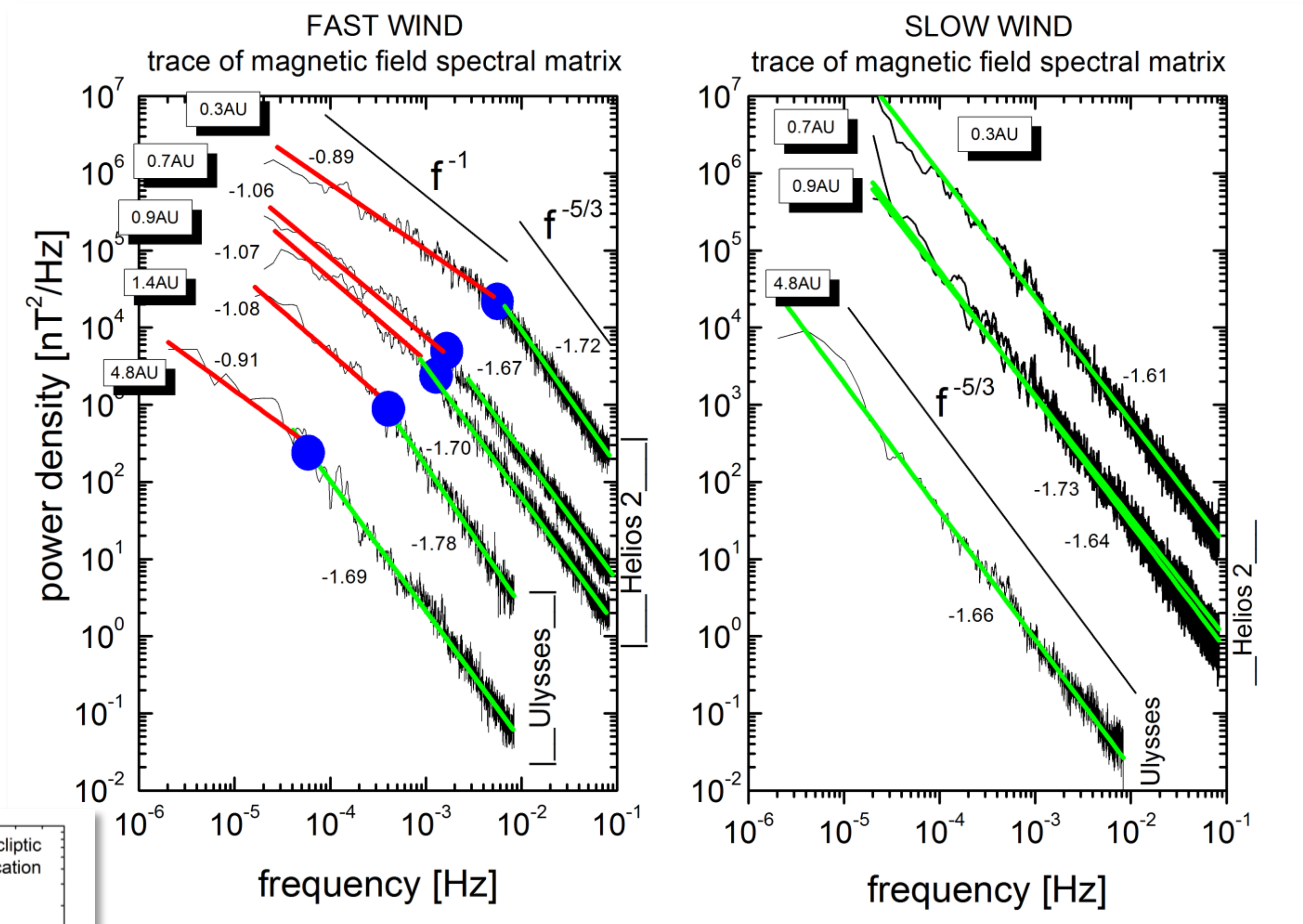
$\lambda_T \sim 2.4\cdot10^3$ km
$\lambda_C \sim 1.3\cdot10^6$ km

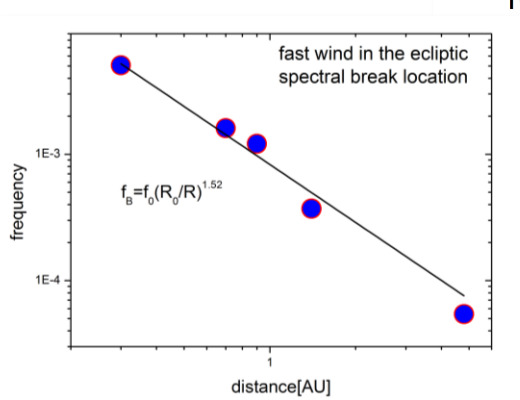
$$R_m^{eff} = \left(\frac{\lambda_C}{\lambda_T}\right)^2 \approx 2.3\cdot10^5$$

high Reynolds number → turbulent fluid → non-linear interactions expected

The shift of the spectral break suggests the presence of non-linear interactions

(Tu , 1984)

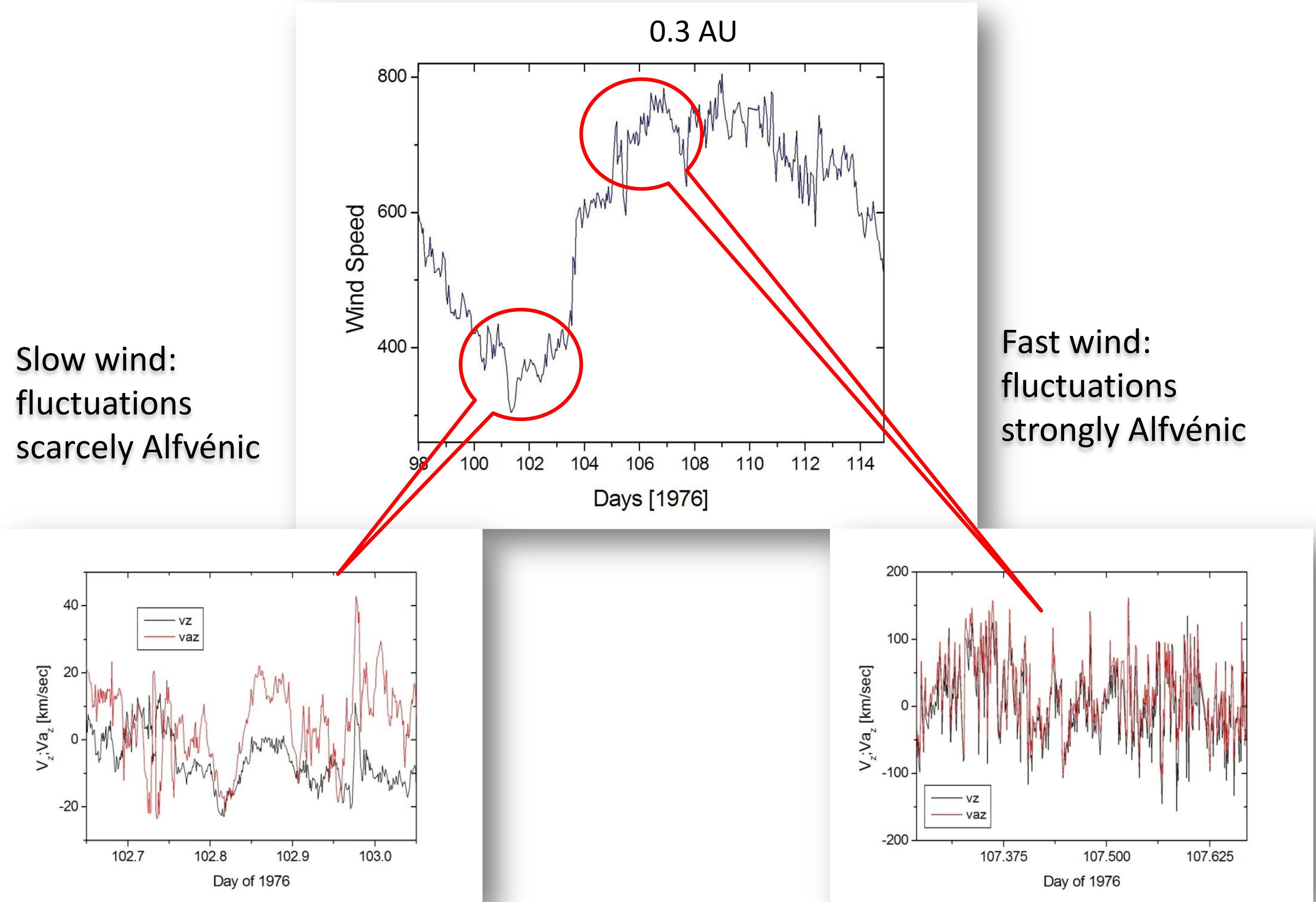




- Non-linear interaction are responsible for this evolution
- More developed turbulence implies larger R_e and larger inertial range

Alfvénic correlations in the solar wind

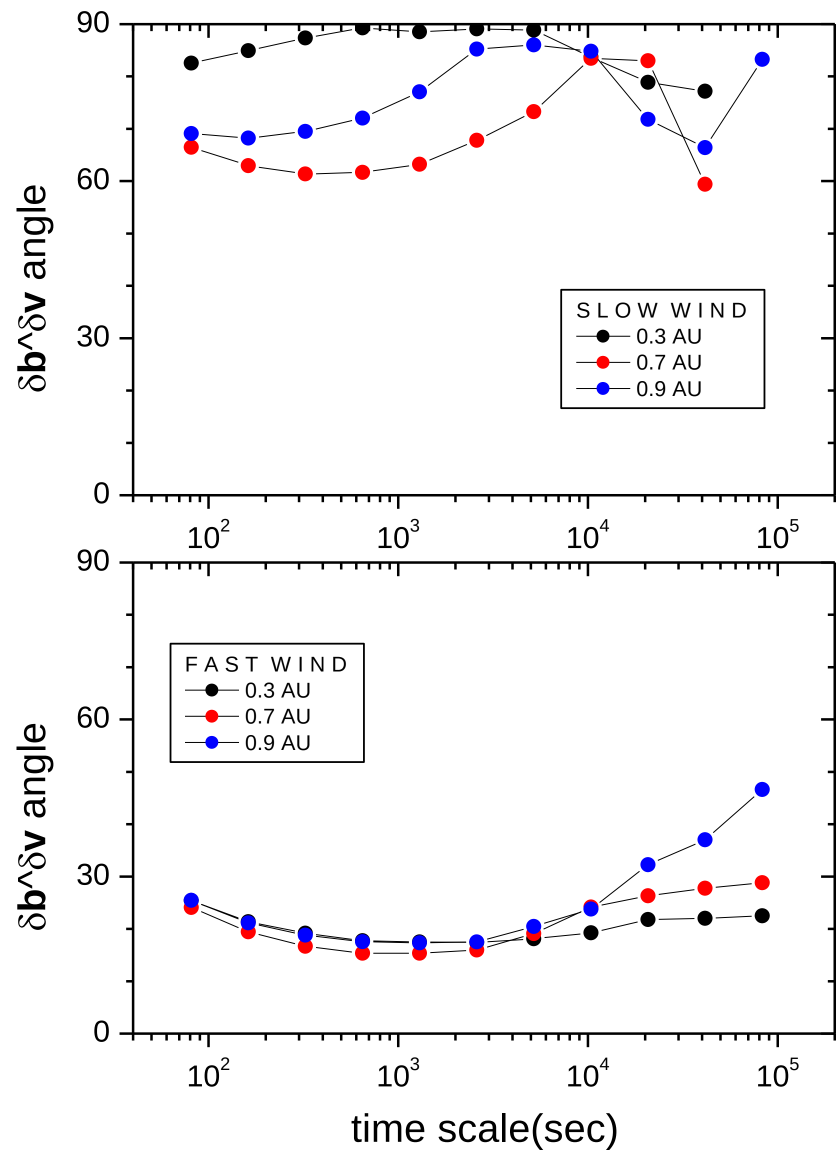
Slow wind: fluctuations scarcely Alfvénic



Fast wind: fluctuations strongly Alfvénic

δB-δV alignment

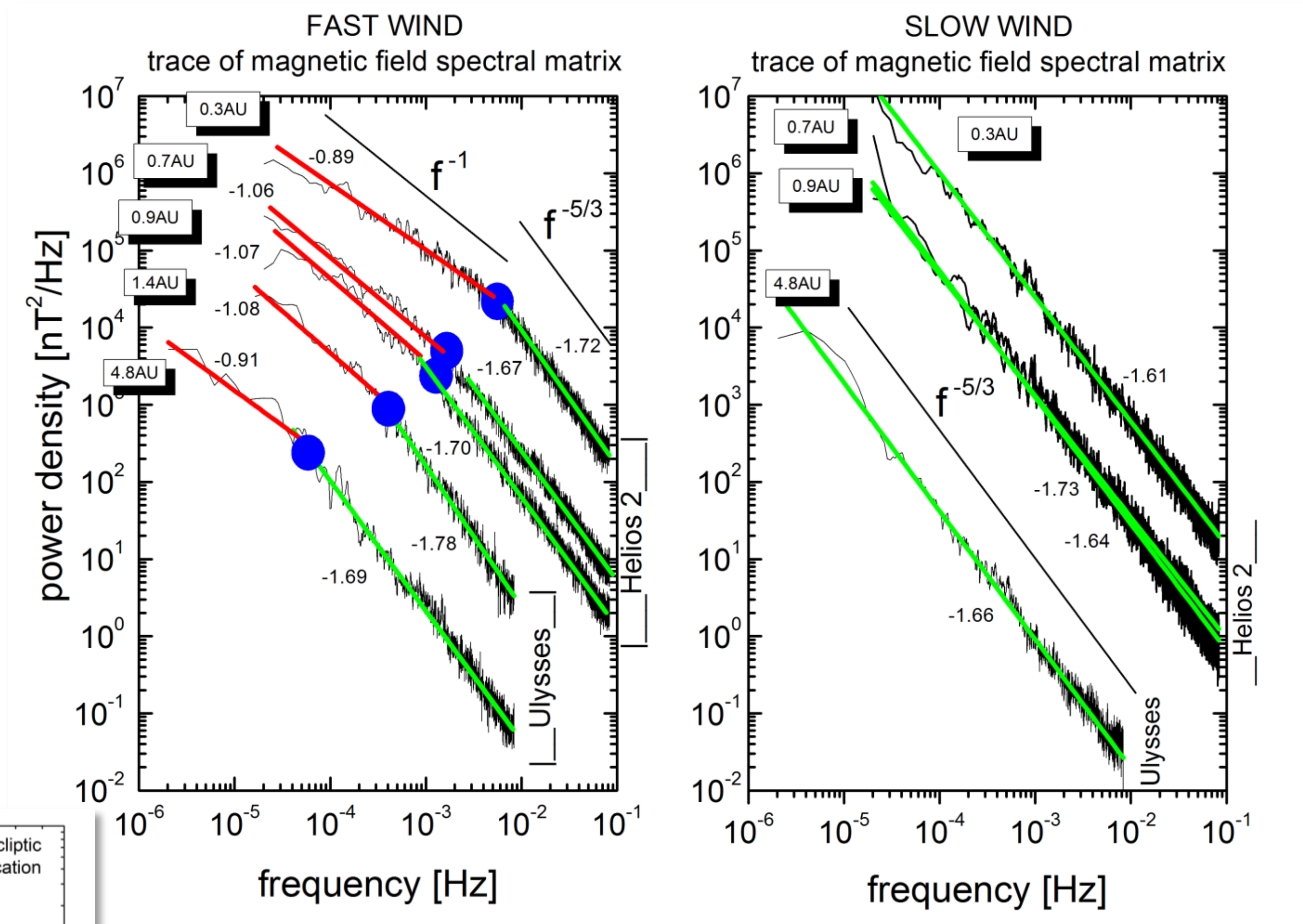
Alfvénicity and radial evolution

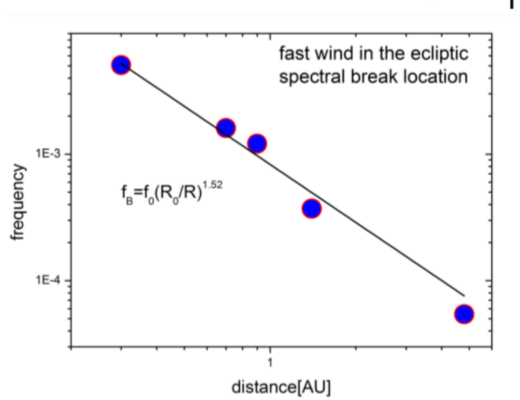


Helios 2 observations

different scales and different heliocentric distances for SLOW and FAST wind

The shift of the spectral break suggests the presence of non-linear interactions
(Tu , 1984)



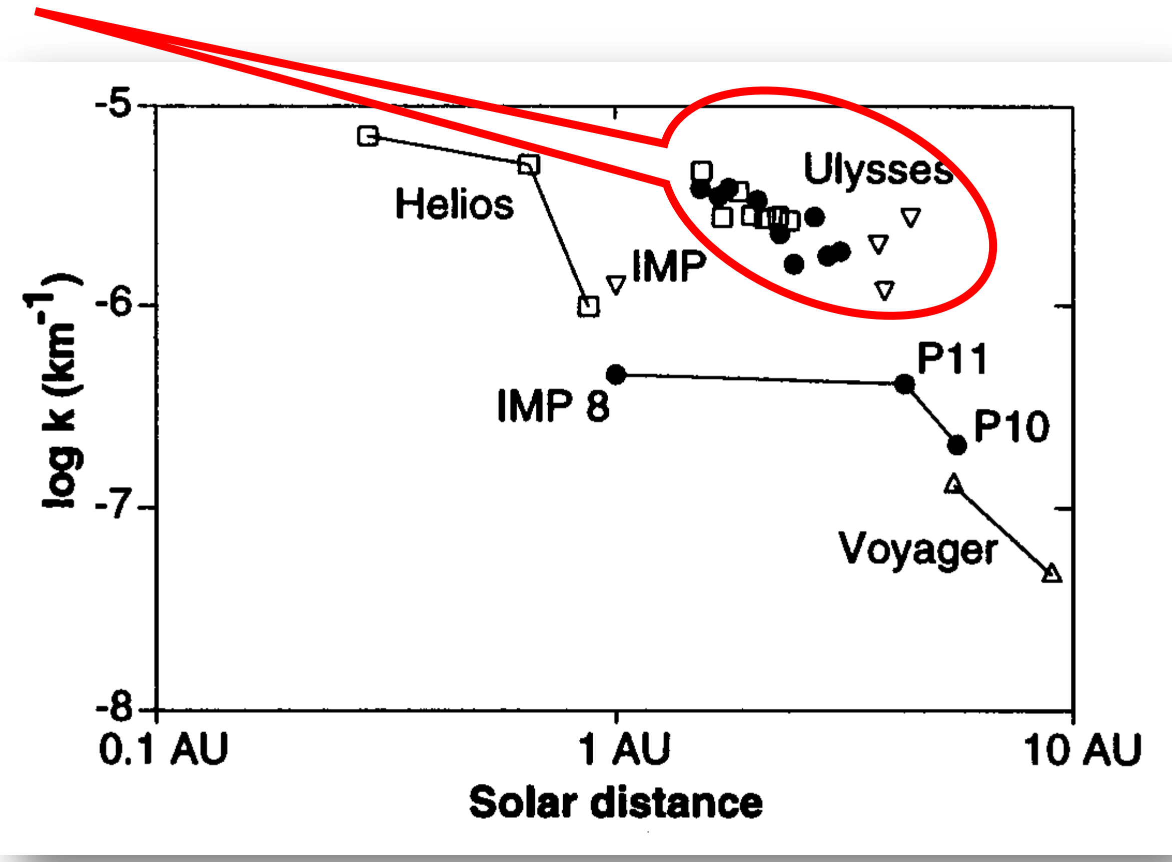


- Non-linear interaction are responsible for this evolution
- More developed turbulence implies larger R_e and larger inertial range

Spectral breakpoint within high latitude solar wind

In the polar wind the breakpoint is at smaller scale than at similar distances in the ecliptic wind.

<u>Thus, spectral evolution in the polar wind is slower than in the ecliptic wind.</u>



Horbury et al., Astron. Astrophys., 316, 333, 1996

To develop non-linear interactions we need to have the simultaneous presence of both Alfvén modes Z+ and Z-

$$\frac{\partial \vec{z}^{\pm}}{\partial t} + (\vec{z}^{\mp} \cdot \nabla)\vec{z}^{\pm} = -\frac{1}{\rho}\nabla\left(p + \frac{B^2}{8\pi}\right) + \nu\nabla^2\vec{z}^{\pm}$$

$$\vec{z}^{\pm} = \vec{u} \pm \vec{b} = \vec{u} \pm \vec{B}/\sqrt{4\pi\rho}$$

$z^{\pm} \rightarrow$ velocity field

P $\rightarrow$ total pressure

$\nu \rightarrow$ kinematic viscosity

$$\vec{\nabla} \cdot \vec{u} = 0$$

Incompressible Navier-Stokes equation for the MHD case

$$R_{\mathrm{v,m}} = \frac{non-linear}{dissipative} \approx 10^5 - 10^6$$

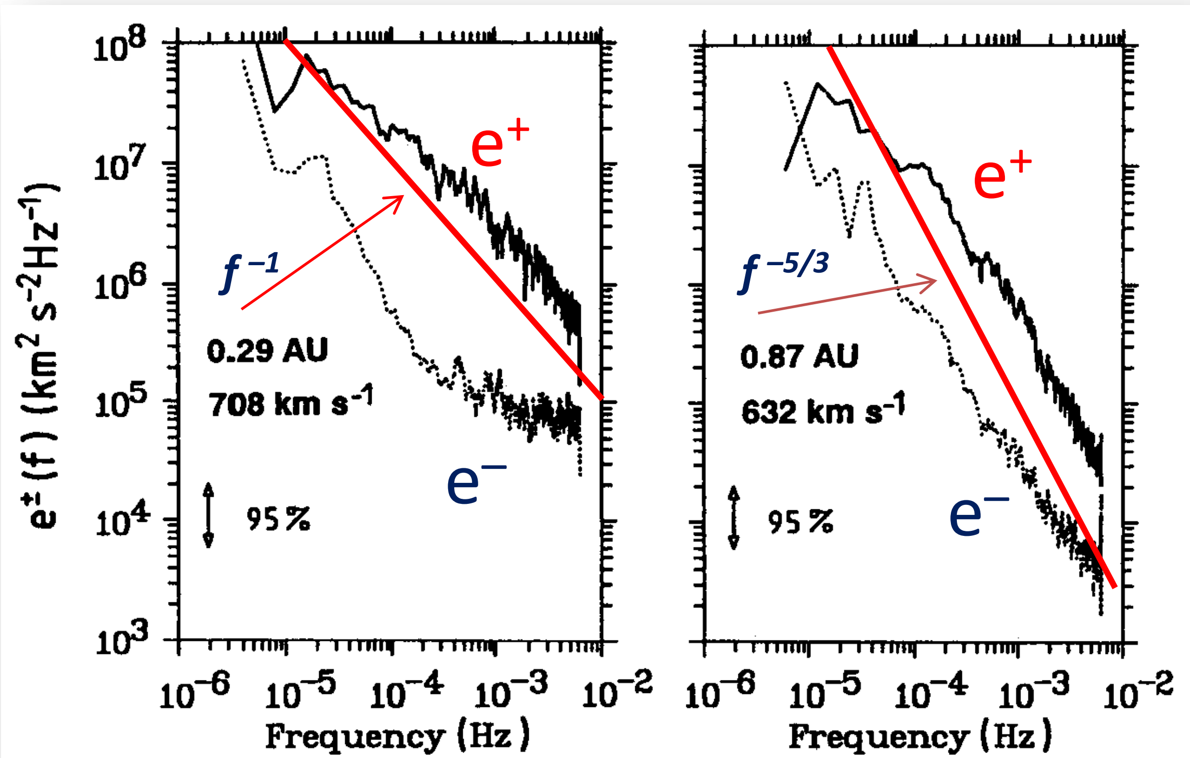
<u>Nonlinear interactions and the consequent energy cascade need both Z+ and Z-</u>

Fast Wind

1. Z^+ are the majority modes
2. Turbulence spectra evolve within fast wind
3. Spectral index towards -5/3

definition
$e^{\pm}(k)=FT[z^{\pm}(t)]$

0.3 AU **0.9 AU**



For increasing distance the e^+ and e^- spectra approach each other (e^+ decreases faster than e^-)

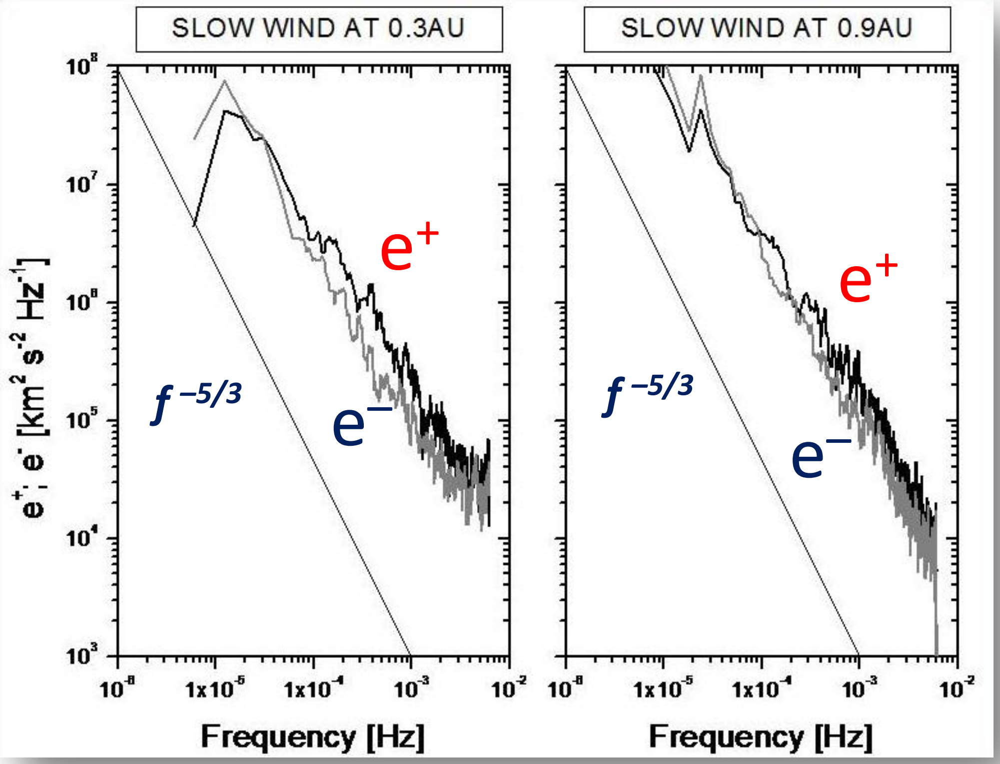
At the same time the spectral slopes evolve, with the development of an extended $f^{-5/3}$ regime.

Marsch and Tu, JGR, 95, 8211, 1990

Slow Wind

1. Quasi equipartition between Z^+ and Z^- modes
2. Turbulence is frozen, does not evolve
3. Spectral index remains at -5/3 (Kolmogorov)

0.3 AU **0.9 AU**

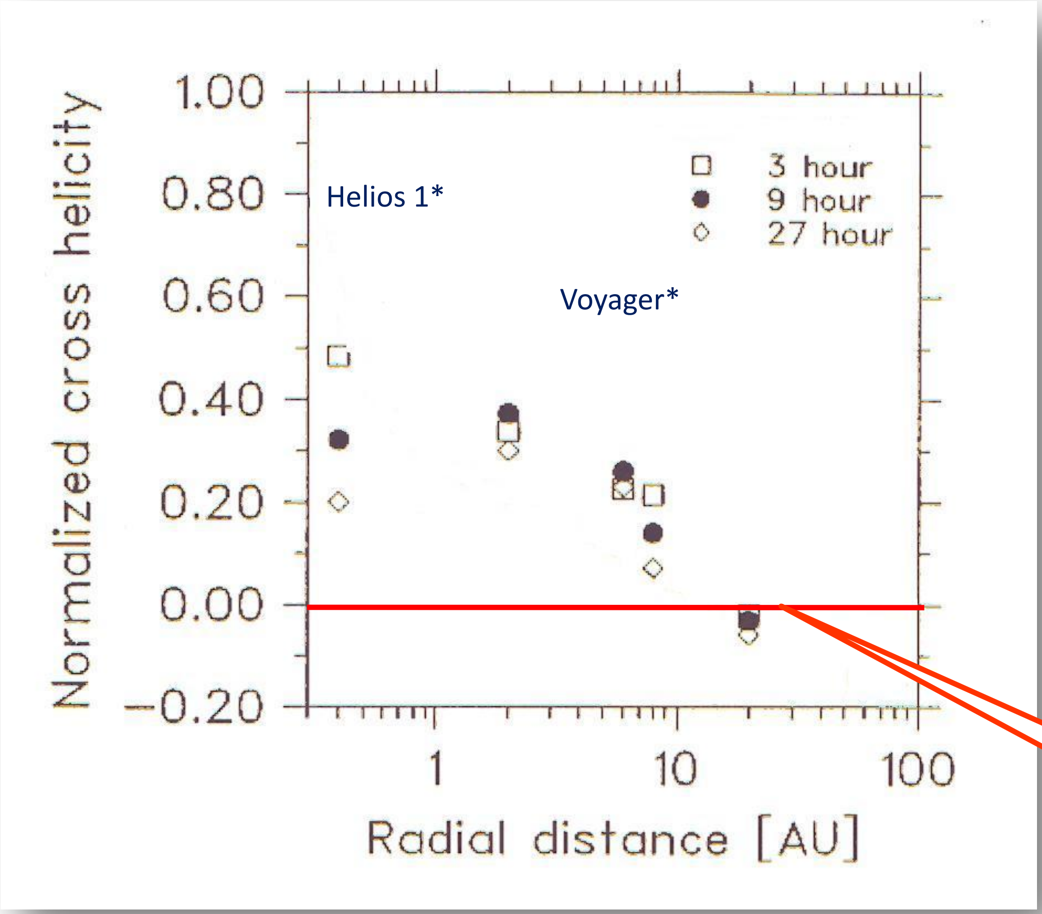


No much radial evolution

Turbulence development reflected in the radial evolution of σ_c in the ecliptic

Normalized cross-helicity

$$\sigma_c = \frac{e^+ - e^-}{e^+ + e^-}$$



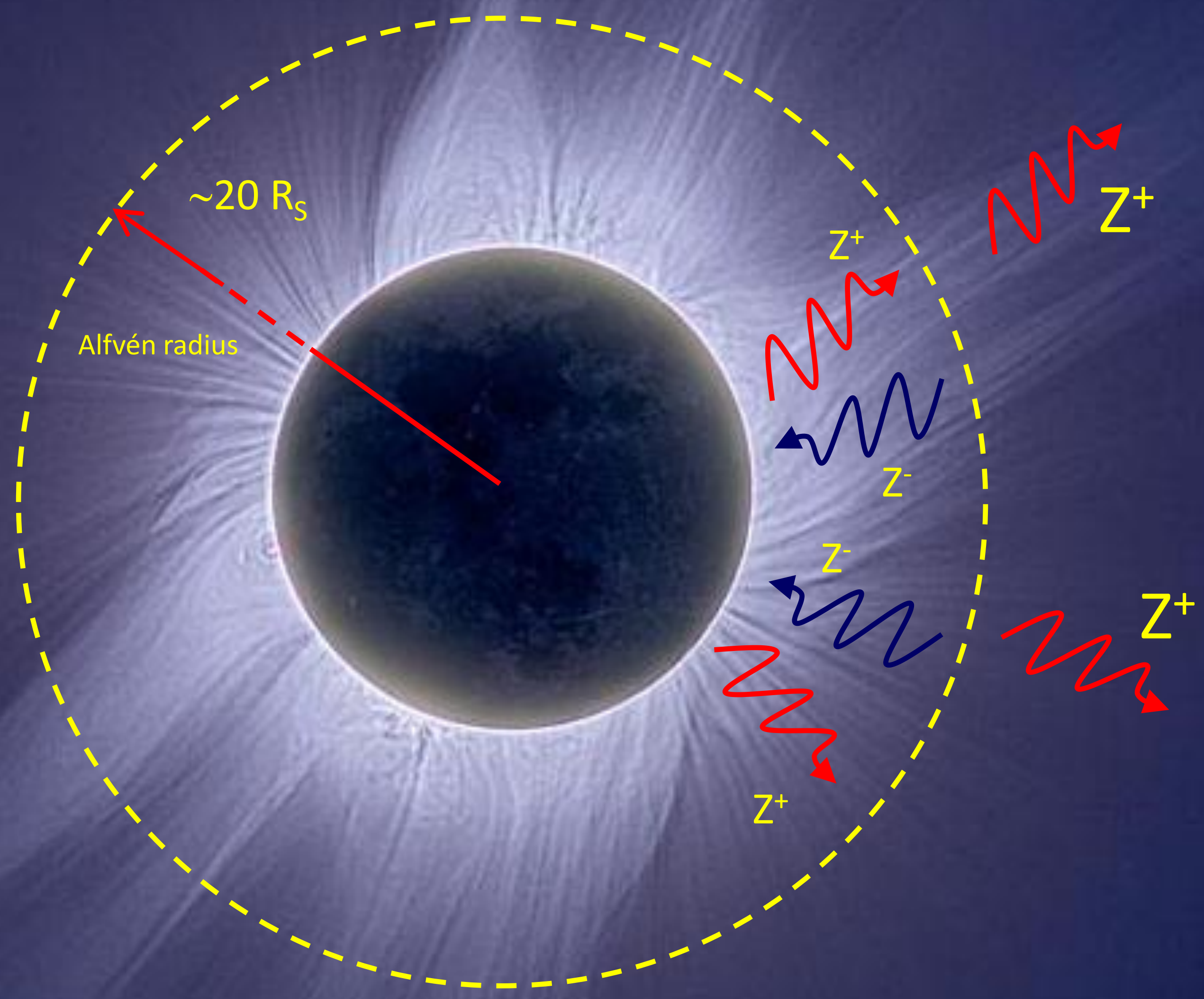
[Adopted from Matthaeus et al., 2004]

Radial depletion of σ_c implies local generation of e^- modes

$\sigma_C \rightarrow 0$

*mixing fast and slow wind

Different origin for Z^+ and Z^- modes in interplanetary space



Outside the Alfvén radius we need Z^- modes in order to have

$$\left(\vec{Z}^{\mp}\cdot\nabla\right)\vec{Z}^{\pm}\neq 0$$

Need for a mechanism able to generate Z^- modes locally

Turbulence development reflected in the radial evolution of σ_c in the ecliptic

Normalized cross-helicity

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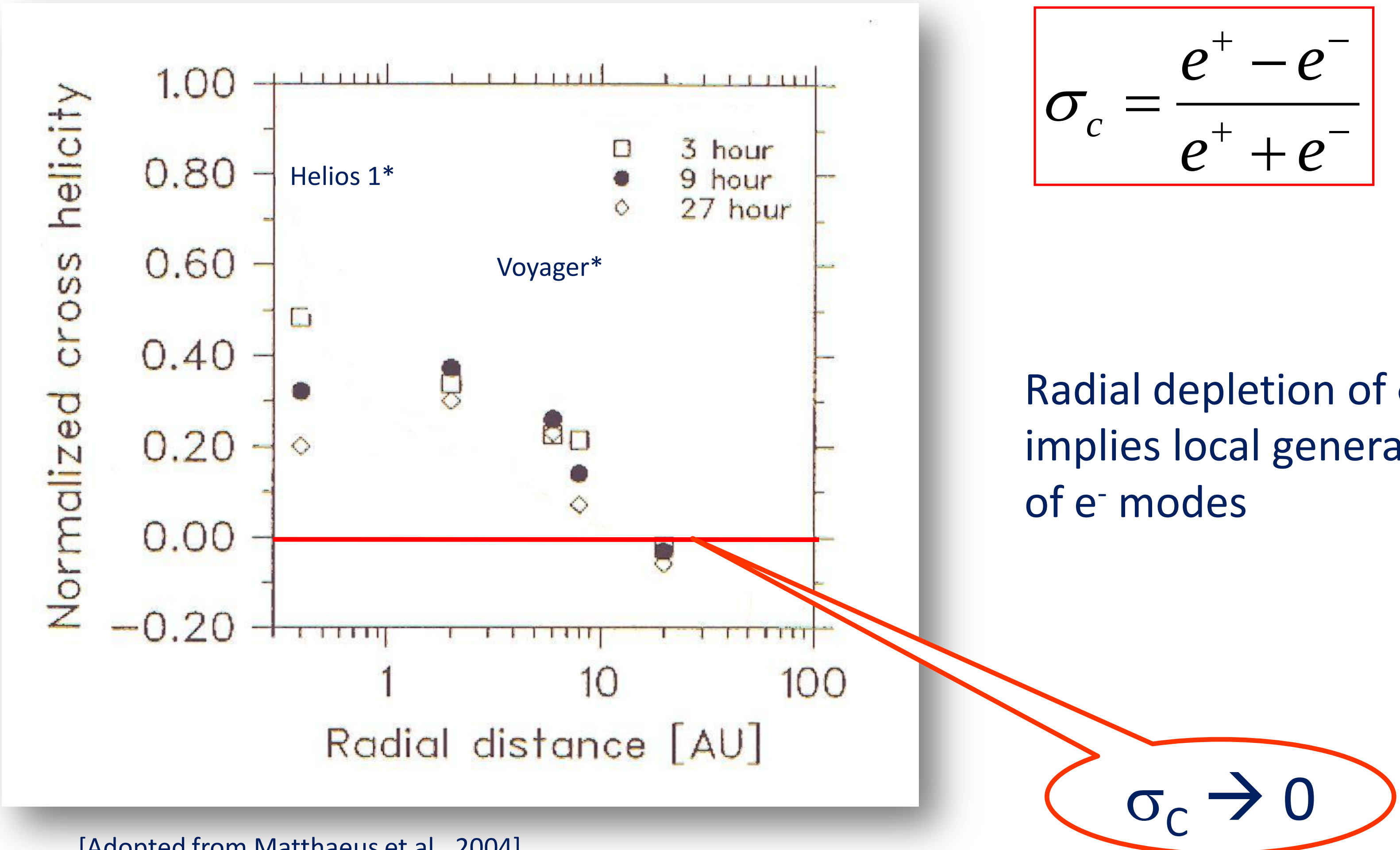

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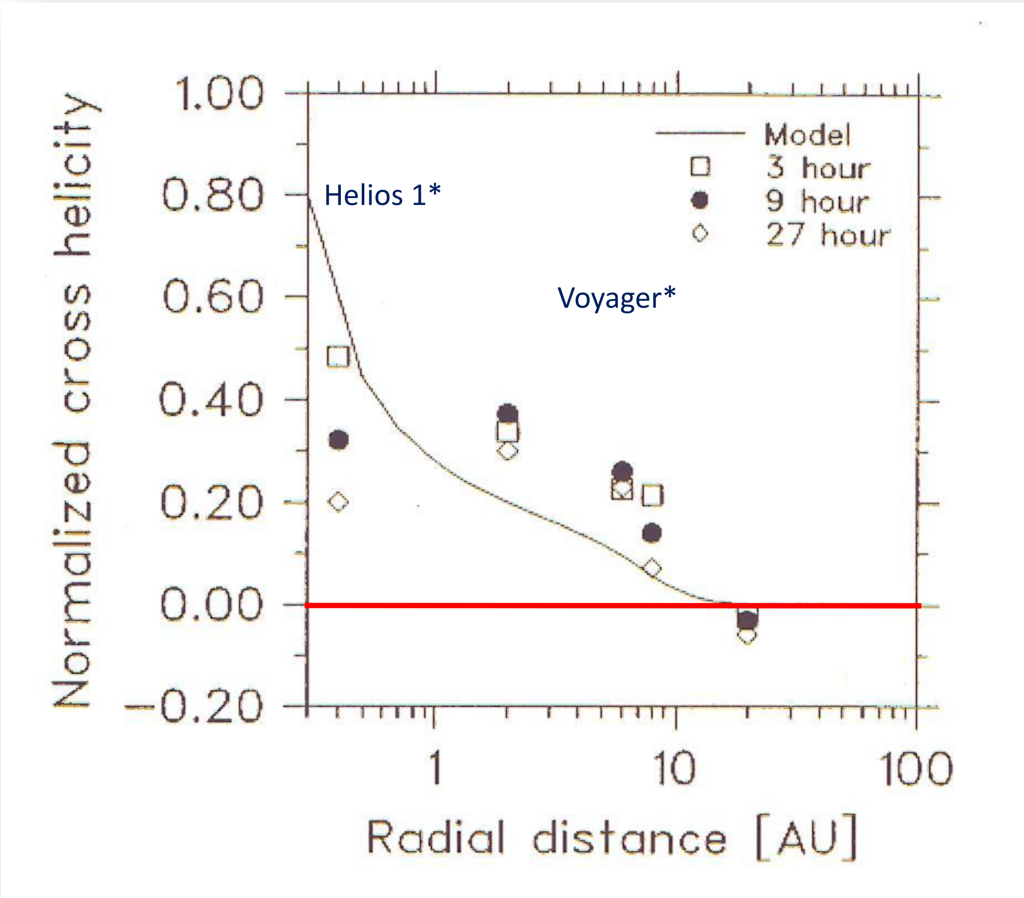


[Adopted from Matthaeus et al., 2004]

$$\sigma_c = \frac{e^+ - e^-}{e^+ + e^-}$$

To fit the radial behavior of σ_c Matthaeus et al (2004) proposed a mechanism based on Velocity shear and dynamic alignment

*mixing fast and slow wind

velocity shear :

(Coleman, 1968)

Quickly generates Z^- modes contributing to decrease the alignment between B and V → $|\sigma_C|$ <u>decreases</u>

dynamic alignment

(Dobrowolny et al., 1980)

Same energy transfer rate for dZ^+ and dZ^- along the spectrum, towards dissipation. An initial umbalance $dZ^+ >> dZ^-$ would end up in the disappearance of the minority modes dZ^- → $|\sigma_C|$ <u>increases</u>

Turbulence generation in the ecliptic: velocity shear mechanism

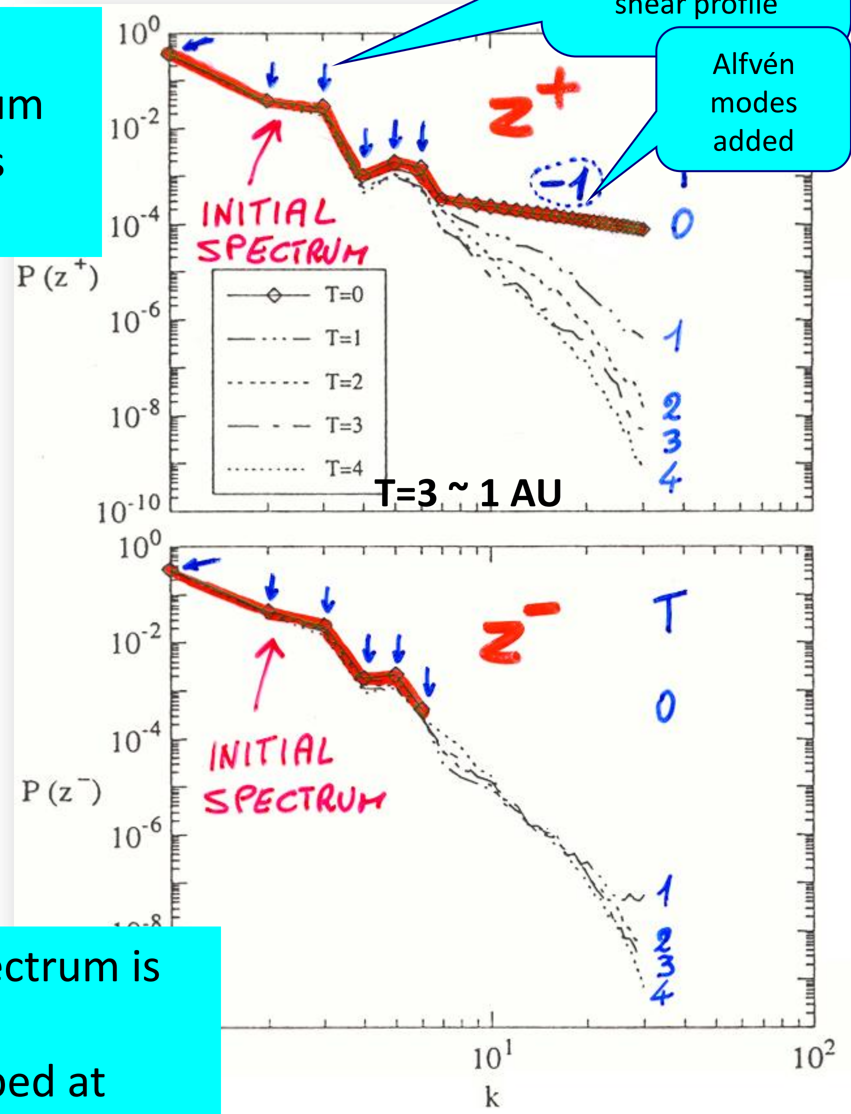
(Coleman 1968)

The z^+ spectrum evolves slowly

The 6 lowest Fourier modes of B and V define the shear profile

Alfvén modes added

- Solar wind turbulence may be locally generated by non-linear processes at velocity-shear layers.
- Magnetic field reversals speed up the spectral evolution.

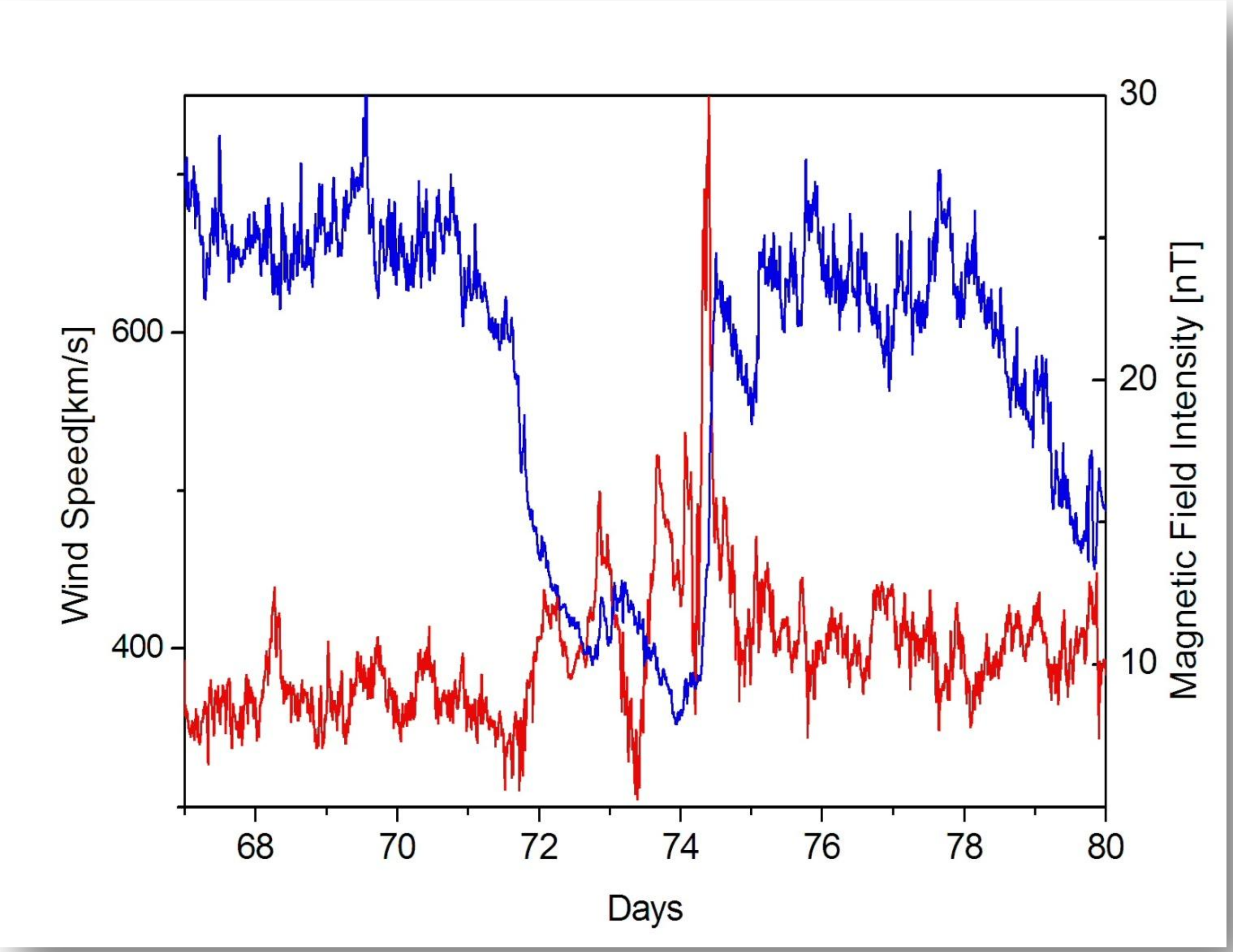


This process might have a relevant role in driving turbulence evolution in low-latitude solar wind, where a fast-slow stream structure and reversals of magnetic polarity are common features.

A z^- spectrum is quickly developed at high k

2D Incompressible simulations by Roberts et al., Phys. Rev. Lett., 67, 3741, 1991

Typical velocity shear region



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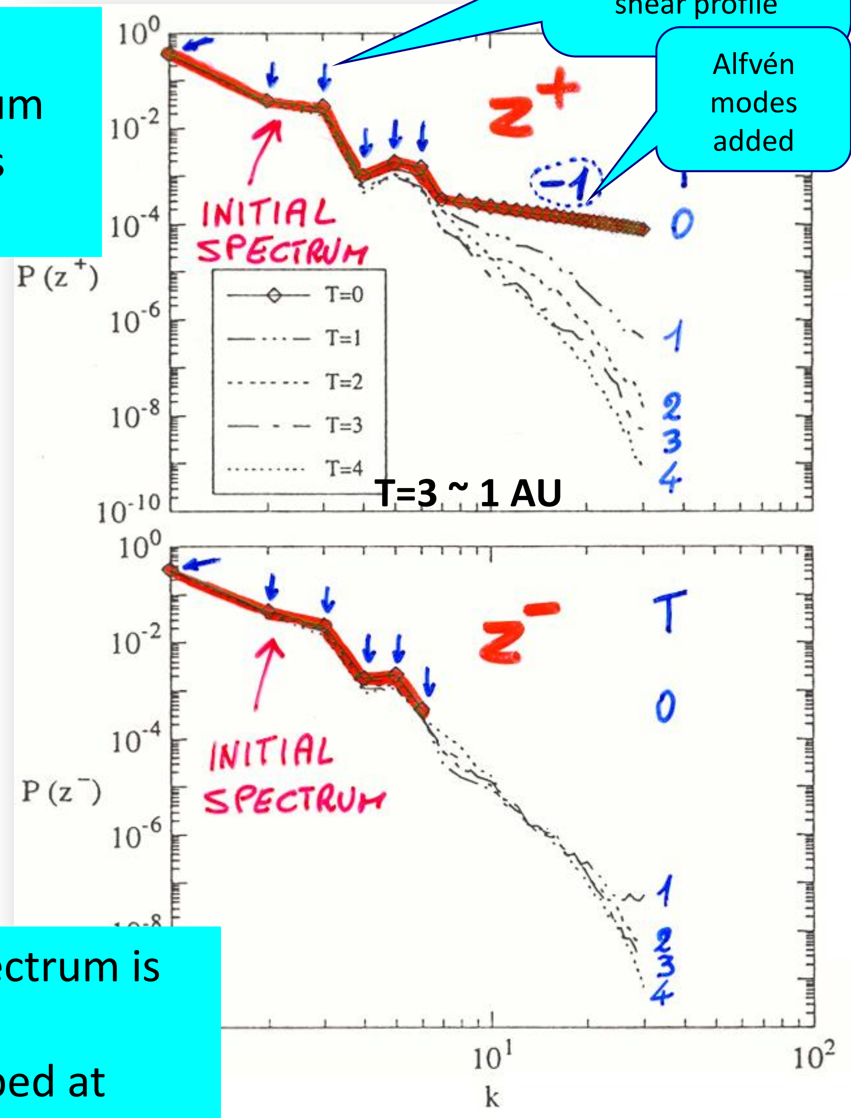

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Dynamic alignment

(Dobrowolny et al., 1980)

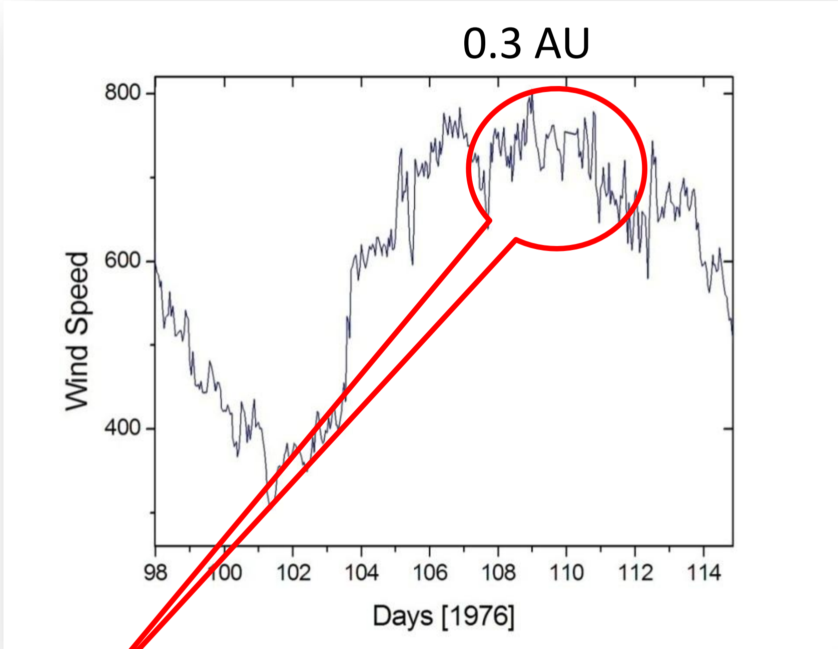
This model was stimulated by apparently contradictory observations recorded close to the sun by Helios:

1. observation of $\boldsymbol{\sigma_c \sim 1}$ means correlations of only one type (δZ^+) ⇒ absence of non-linear interactions

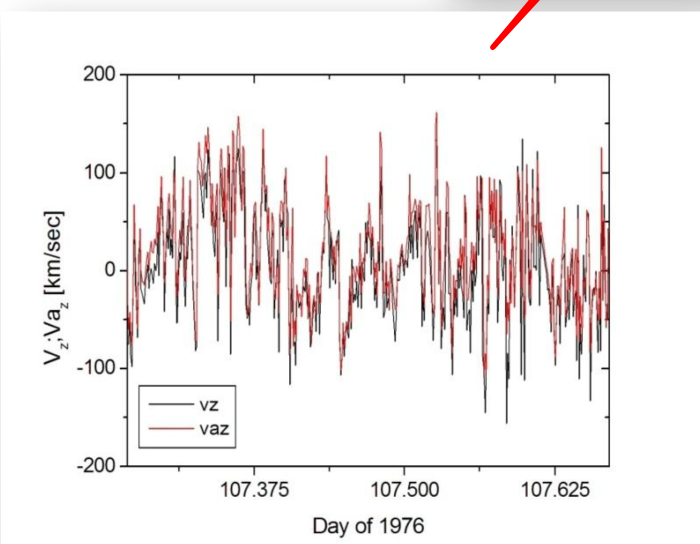
2. turbulent spectrum clearly observed ⇒ presence of non-linear interactions

?

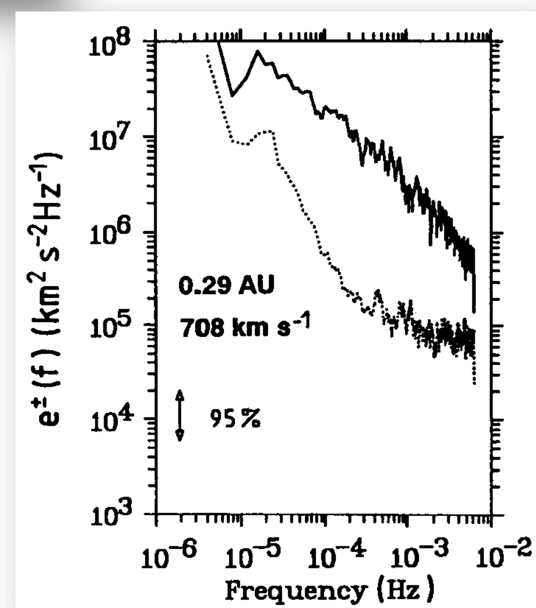
Alfvénic correlations in the solar wind



Fast wind fluctuations strongly Alfvénic



Outward modes largely dominate



Dynamic alignment

(Dobrowolny et al., 1980)

Interactions between Alfvénic fluctuations are local in **k**-space

We can define 2 different time-scales for these interactions

$$t_i^{\pm} \sim \frac{\ell}{\delta Z_\ell^{\mp}}$$

$$t_a^{\pm} \sim \frac{\ell}{C_a}$$

The Alfvén effect increases the non-linear interaction time

$$T_\ell^{\pm} \sim t_i^{\pm} \frac{t_i^{\pm}}{t_A} \rightarrow \frac{\ell C_A}{(\delta Z_\ell^{\mp})^2}$$

We can define an energy transfer rate

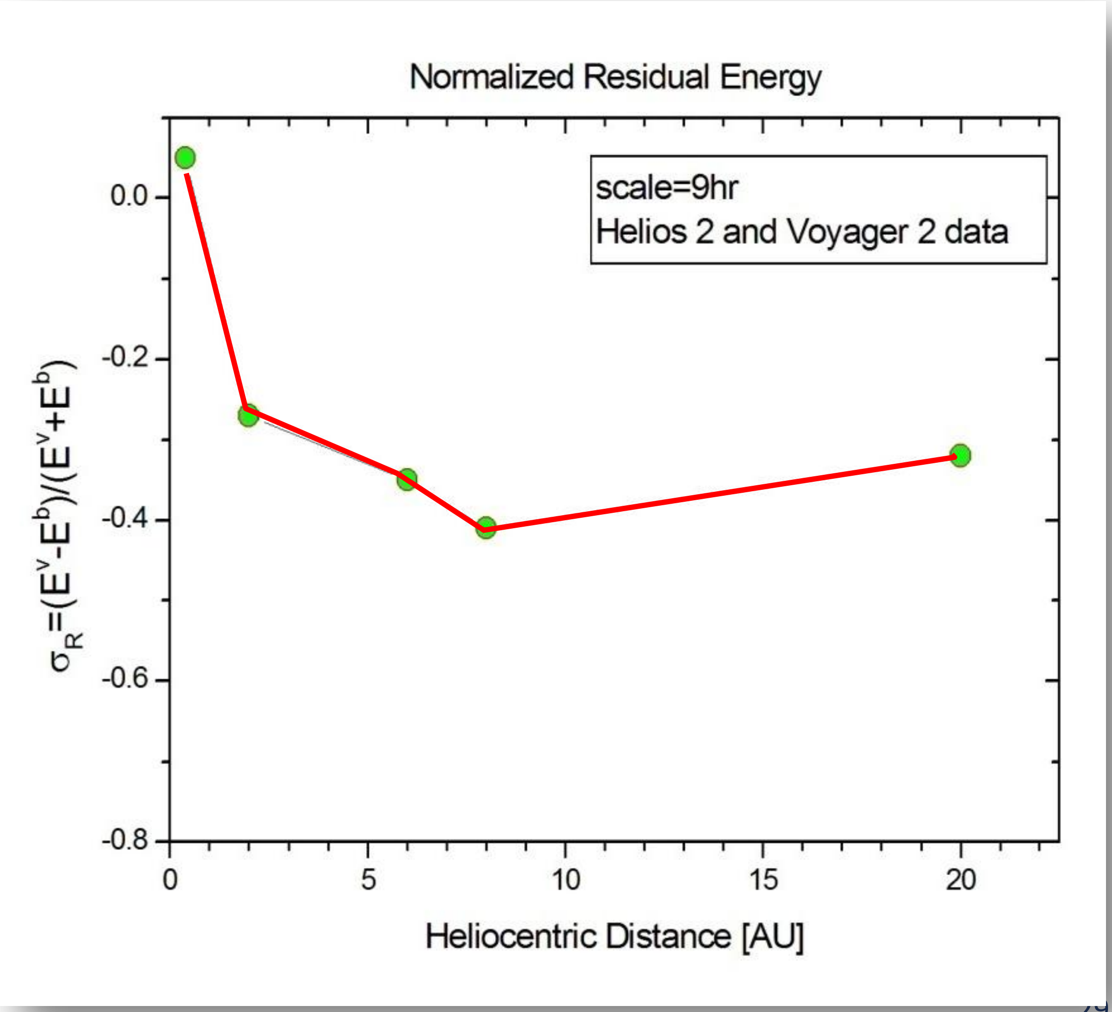
$$\Pi_\ell^{\pm} \sim \frac{(\delta Z_\ell^{\pm})^2}{T_\ell^{\pm}} \sim \ell^{-1} C_A^{-1} (\delta Z_\ell^{\pm})^2 (\delta Z_\ell^{\mp})^2$$

The energy transfer rate is the same for dZ^+ and dZ^-
An initial unbalance between dZ^+ and dZ^- , as observed close to the Sun, would end up in the disappearance of the minority modes dZ^- towards a total alignment between dB and dV as the wind expands

However, velocity shear and dynamic alignment do not explain the radial behavior of the normalized residual energy σ_R

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}$$

Magnetic energy e^b dominates on kinetic energy e^v during the wind expansion



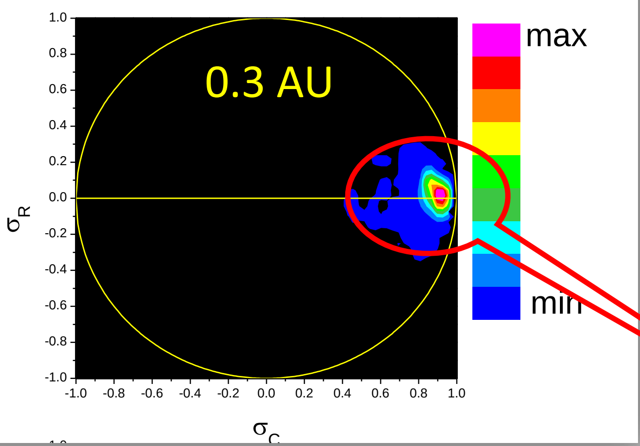
Adapted from Roberts et al., JGR, 95, 4203, 1990

The following analysis will focus on this problem since the presence of magnetically dominated fluctuations suggests the presence of advected structures

i.e.

low frequency solar wind fluctuations are not only due to turbulent evolution of Alfvénic modes

Radial evolution of MHD turbulence in terms of σ_R and σ_C (scale of 1hr)



Alfvénic population

$$\sigma_C = \frac{e^+ - e^-}{e^+ + e^-} = \frac{2 < v \cdot b >}{e^v + e^b}$$

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}$$

$$\sigma_C^2 + \sigma_R^2 \leq 1$$

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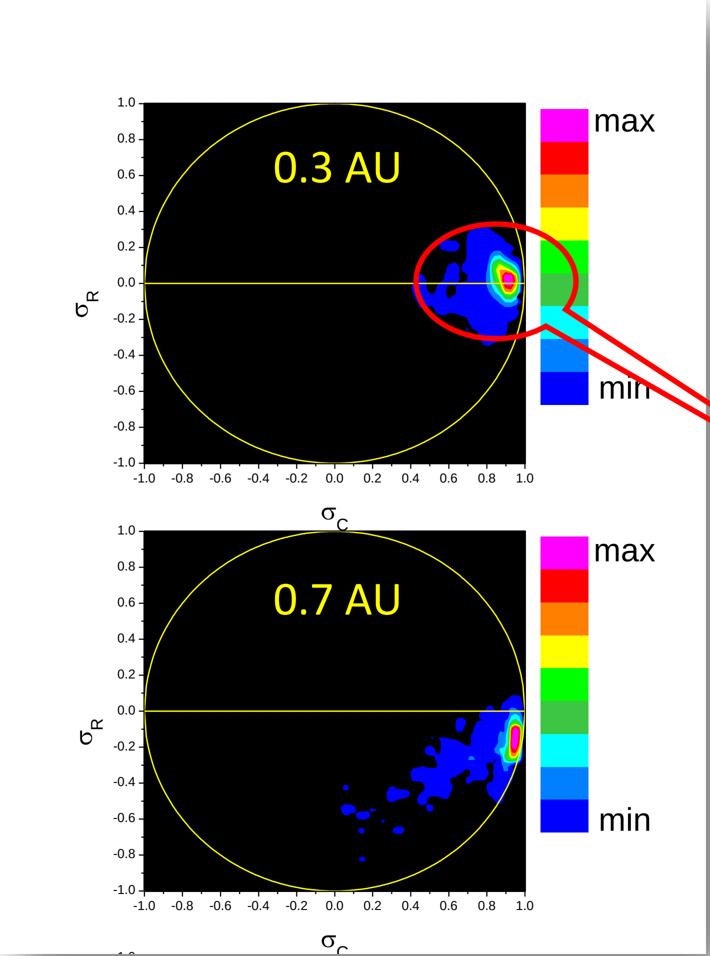

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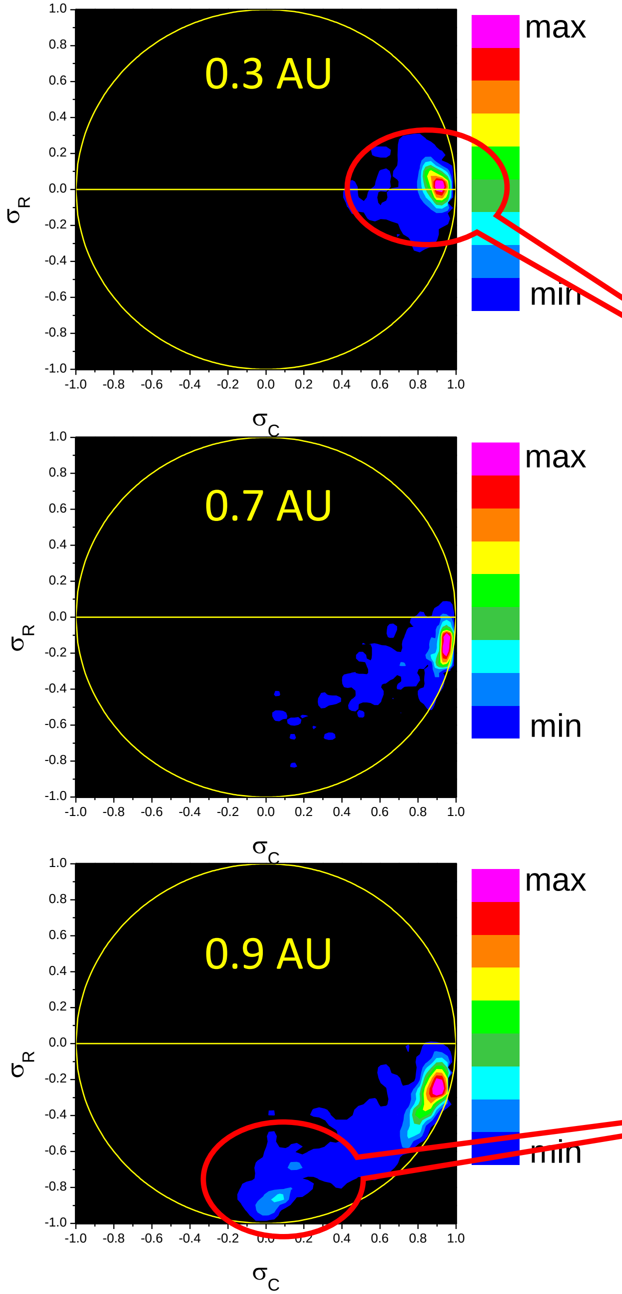

(Bruno et al., 2007)

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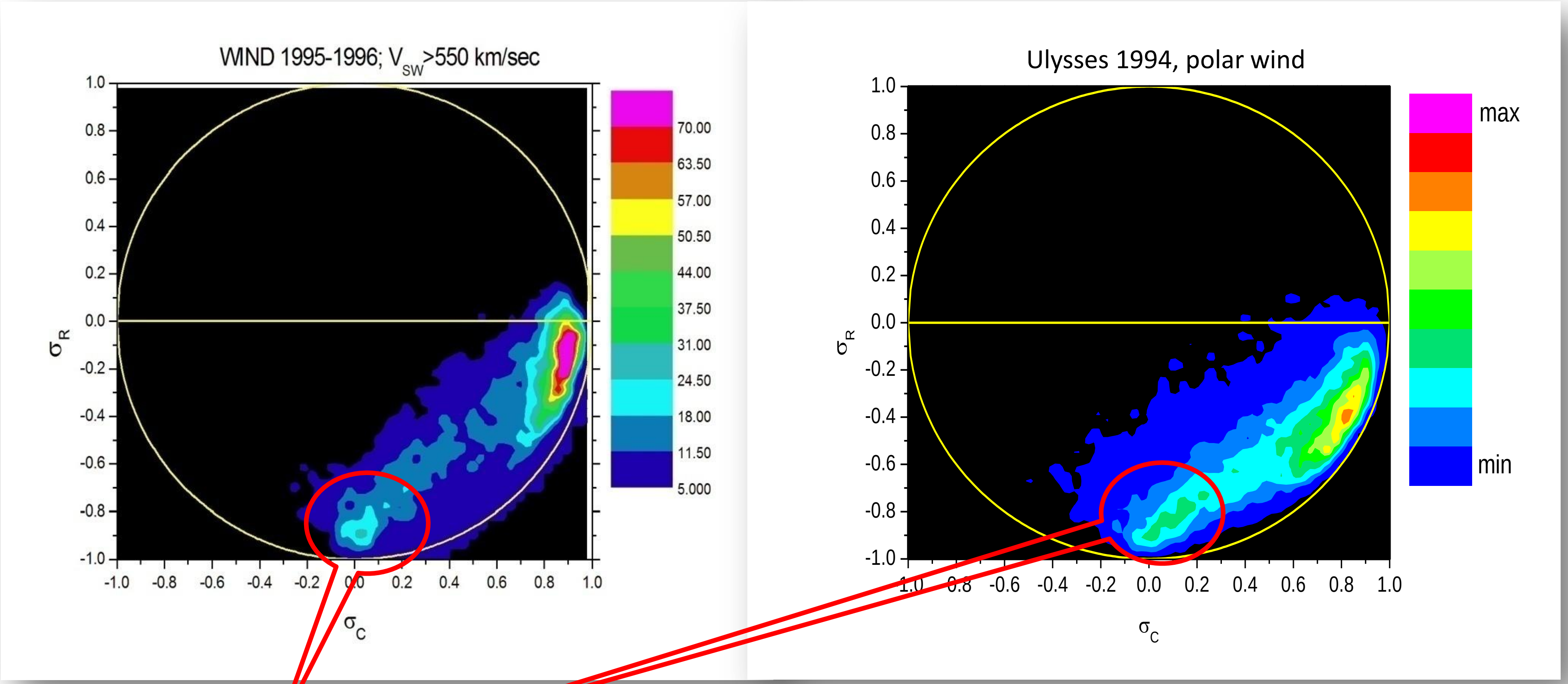
$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}$$

$$\sigma_C^2 + \sigma_R^2 \leq 1$$

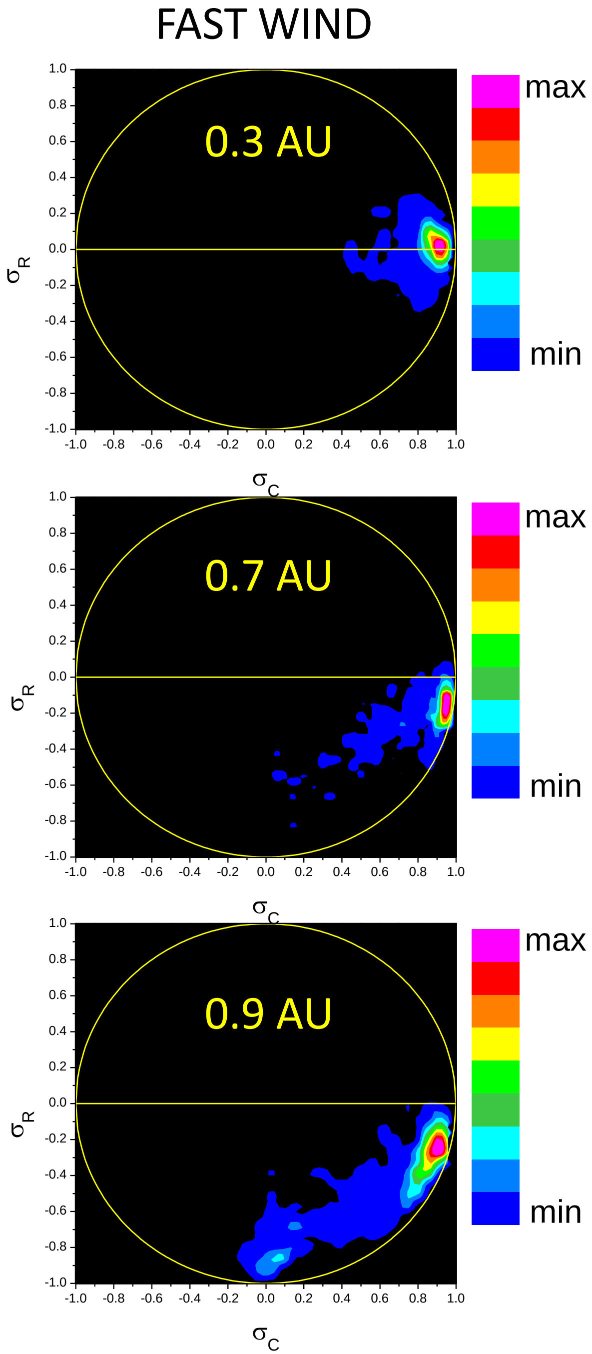
A new population appears, characterized by magnetic energy excess and low Alfvénicity

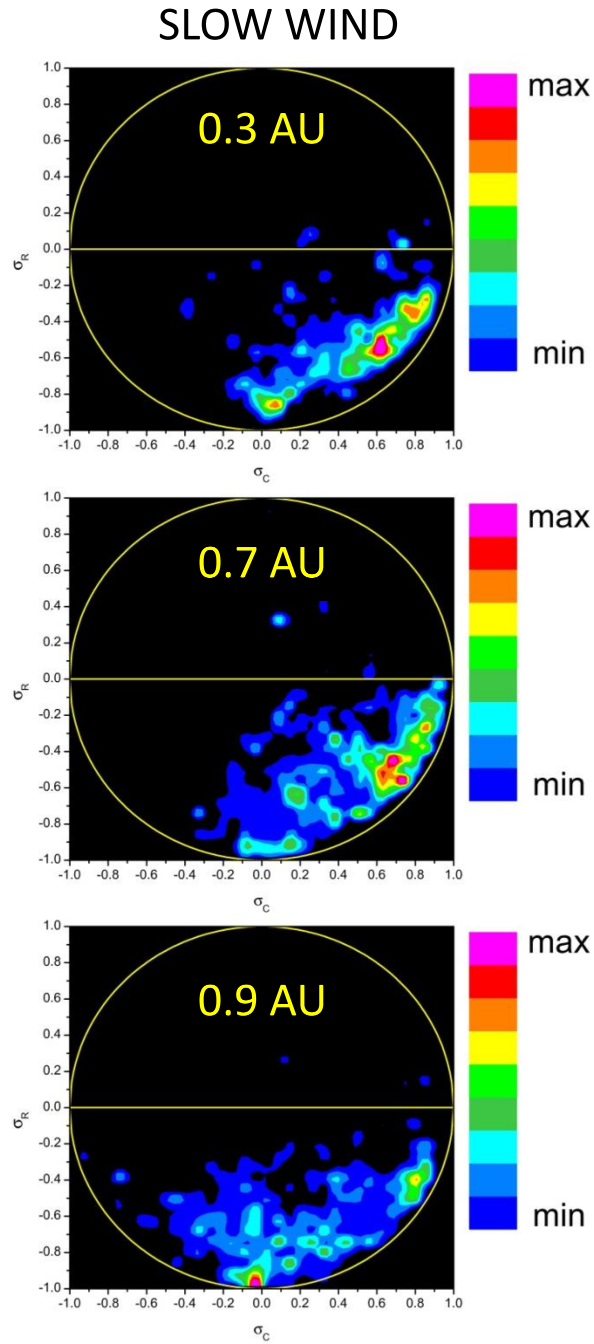
Similar results obtained by WIND at 1 AU and ULYSSES around -75° and at 2.3AU



Fluctuations characterized by magnetic energy excess and low Alfvénicity

this might be the result of turbulence evolution or the signature of underlying advected structure

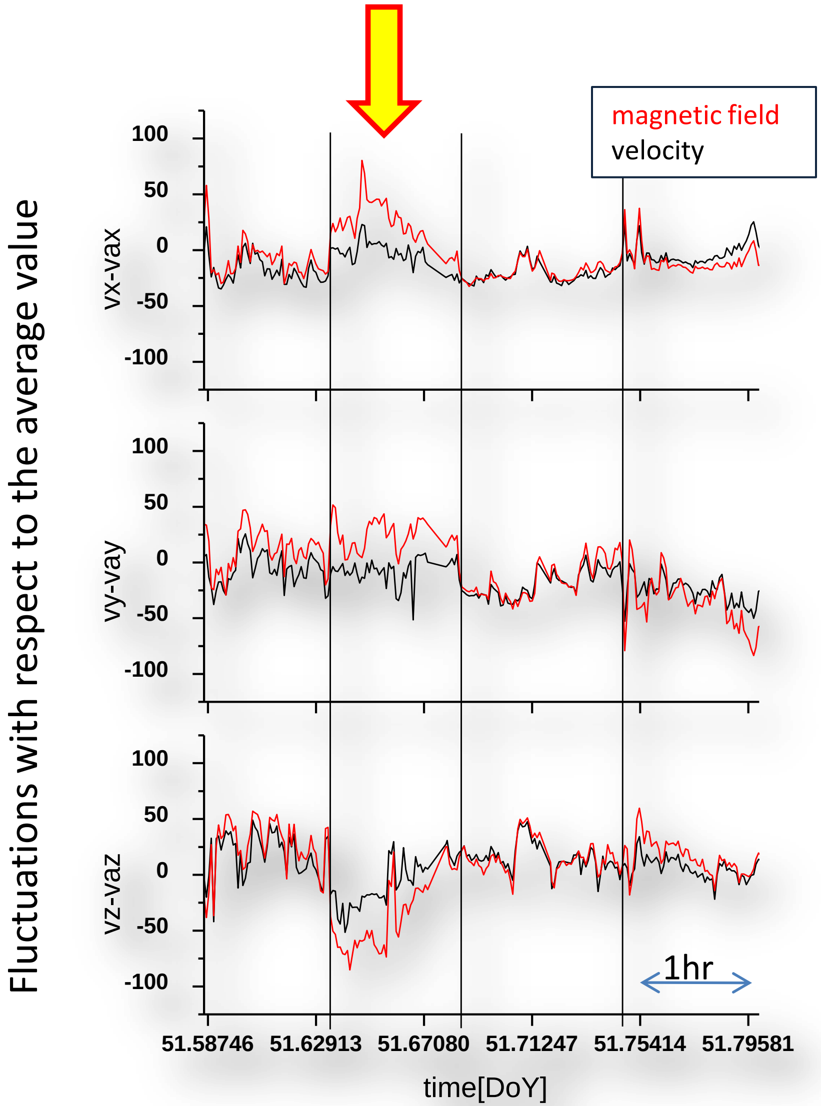


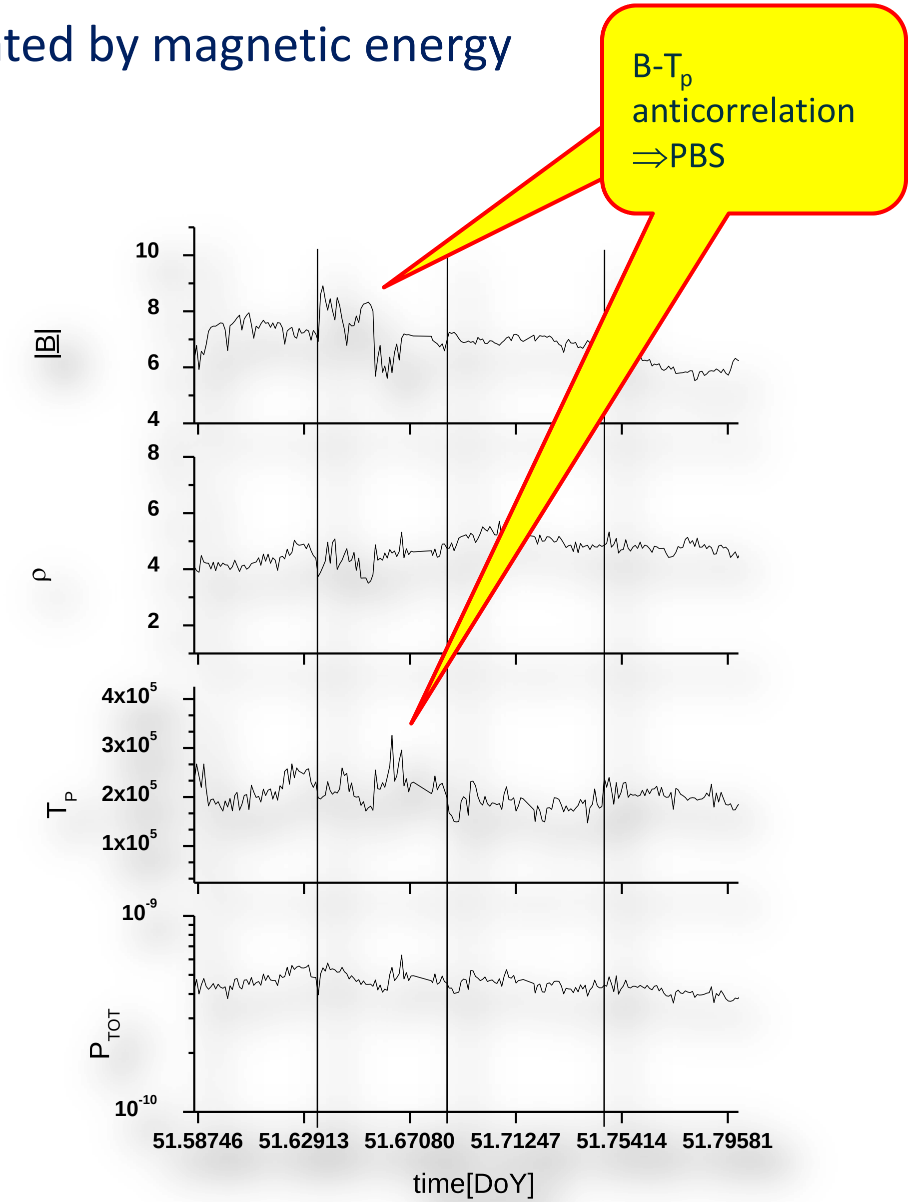


Different situation in Slow-Wind:

- no evolution
- second population already present at 0.3 AU

In particular: typical case dominated by magnetic energy





(Bruno et al., 2007)

remarks

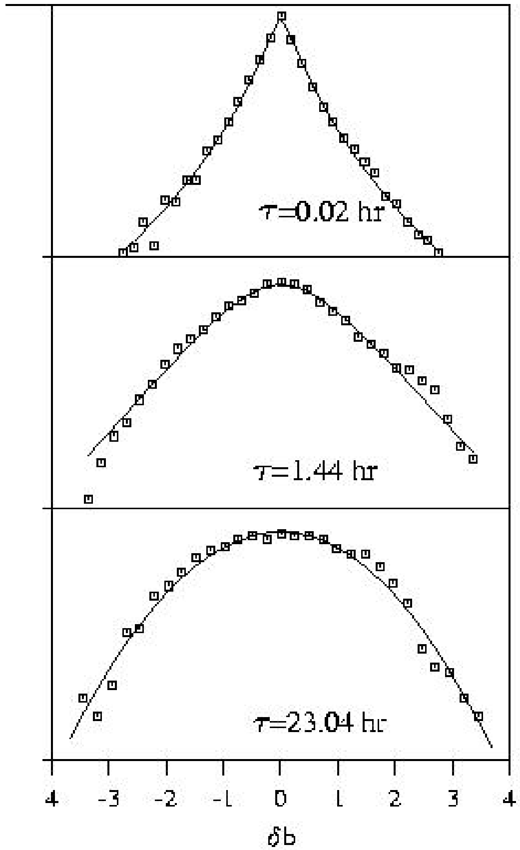
Turbulence mostly made of Alfvénic modes and convected magnetically dominated structures

As the wind expands, convected structures become more important

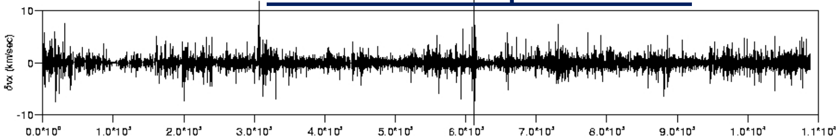
It has been shown that the crossing of these structures affects the selfsimilar character of solar wind fluctuations and causes *anomalous scaling* or *intermittency* (Bruno et al., 2001)

Effect of intermittency on PDFs

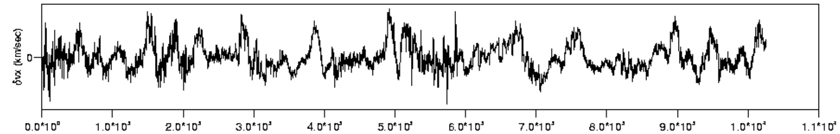
Interplanetary Magnetic Field fluctuations
at three scales



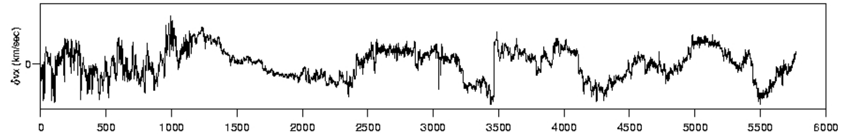
Small scale: stretched exponential



Inertial range: fat tails

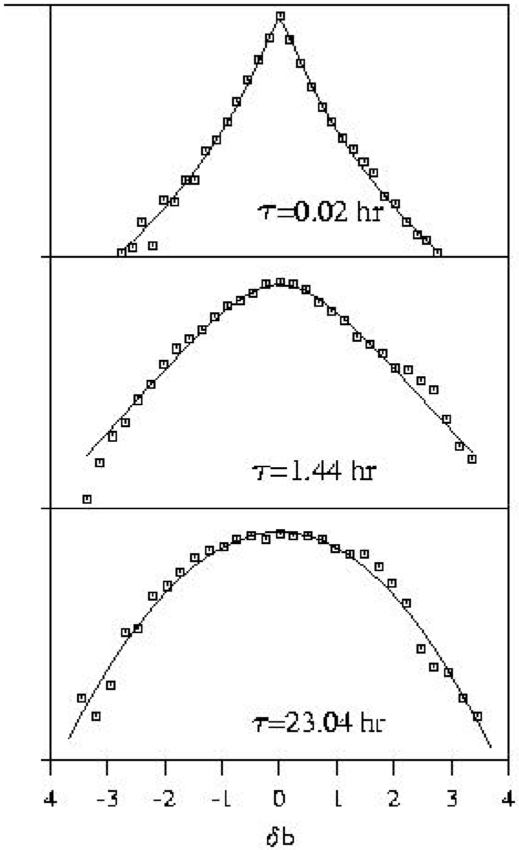


Large scale: nearly Gaussian



PDF's of δv and δb do not rescale

Effect of intermittency on PDFs



“A random function is intermittent at small scales if the flatness grows without bound at smaller and smaller scales” (Frisch, 1995)

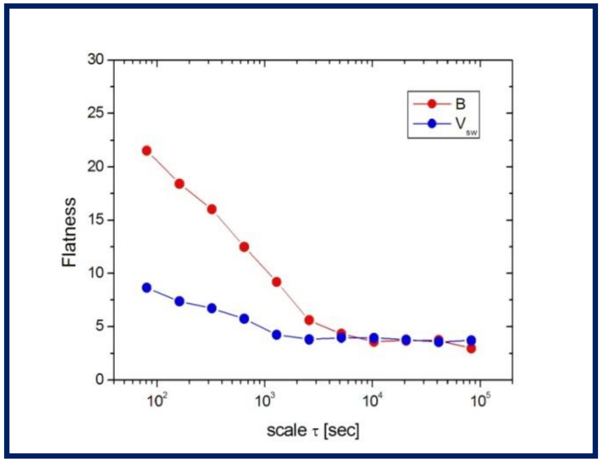
4th order moment or Flatness to estimate Intermittency

$$F_\tau = S_\tau^4/(S_\tau^2)^2$$

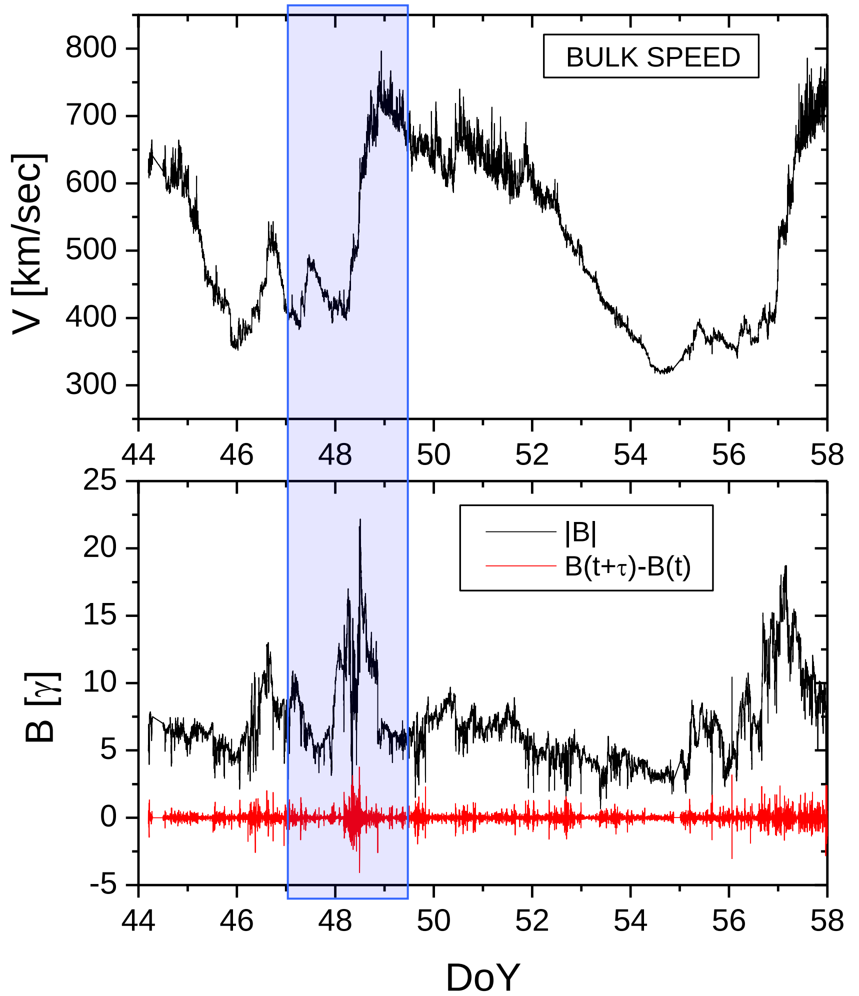
where

$$S_\tau^p = \langle \left(v(t+\tau) - v(t)\right)^p \rangle$$

For a Gaussian statistics $F_t=3$



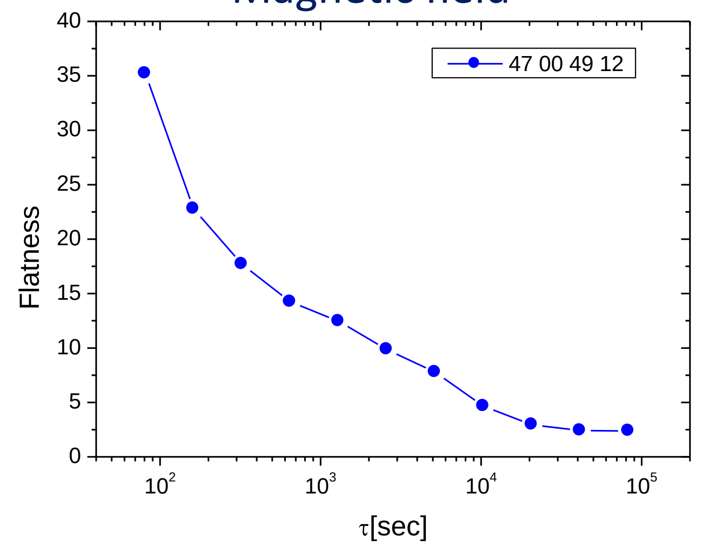
Intermittency along the velocity profile



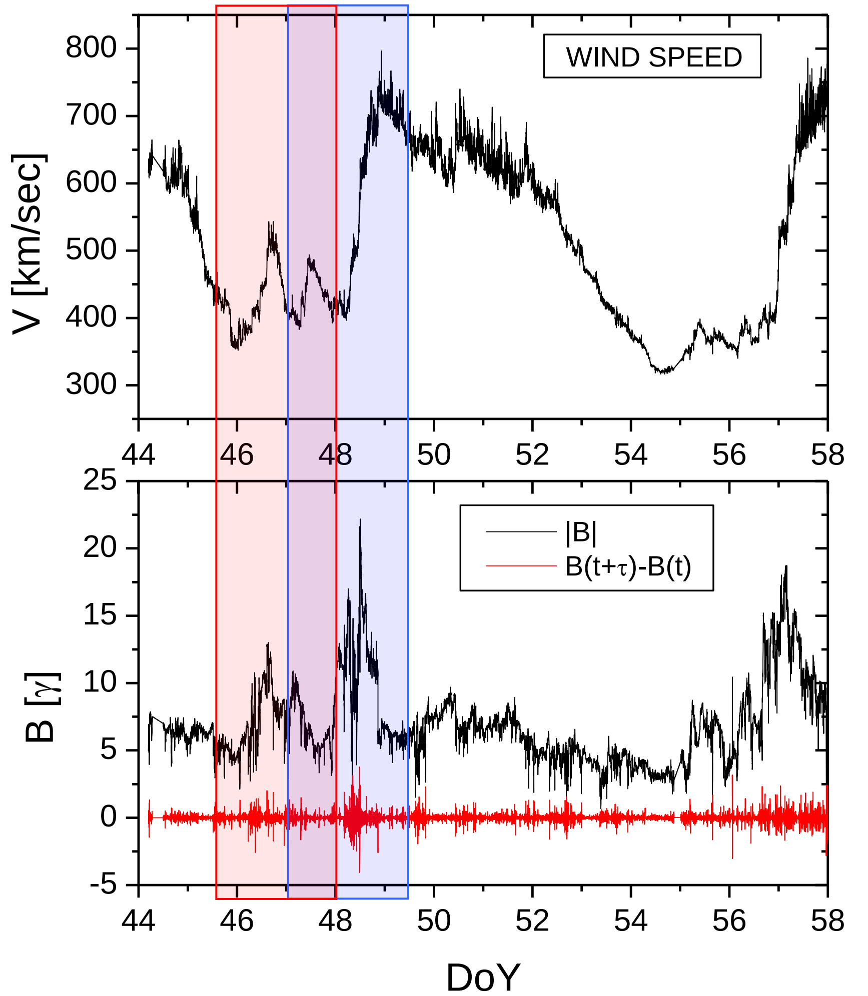
Intermittency strongly depends on the location within the stream

$$F_\tau = S_\tau^4 / (S_\tau^2)^2$$

Magnetic field

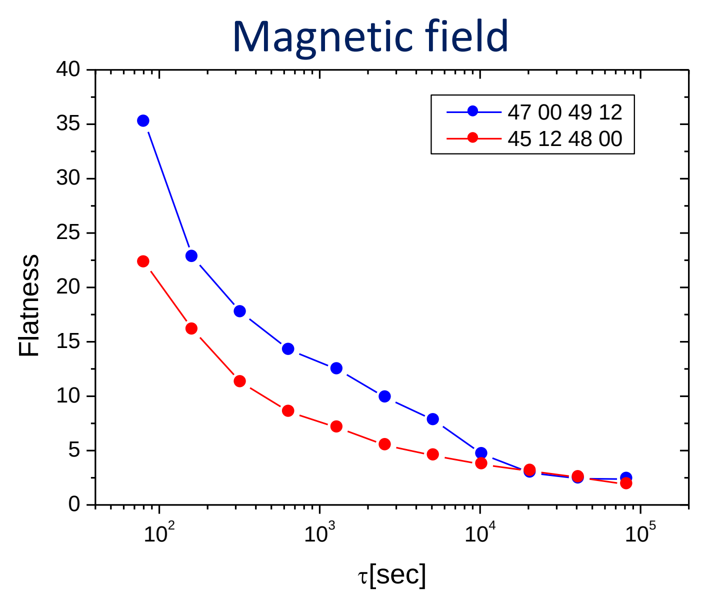


Intermittency along the velocity profile

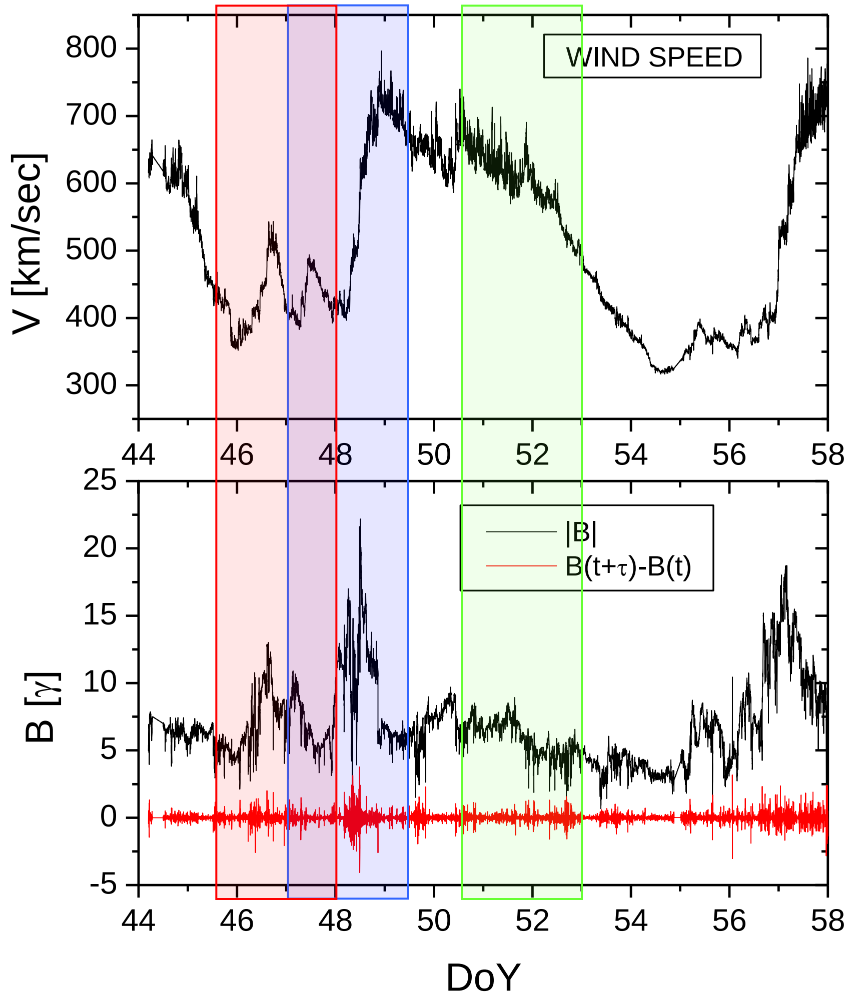


Intermittency strongly depends on the location within the stream

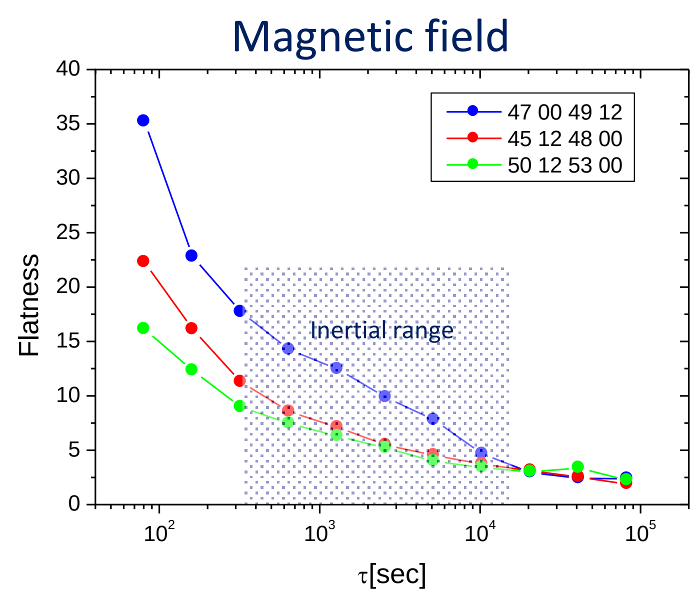
$$F_\tau = S^4_\tau/(S^2_\tau)^2$$



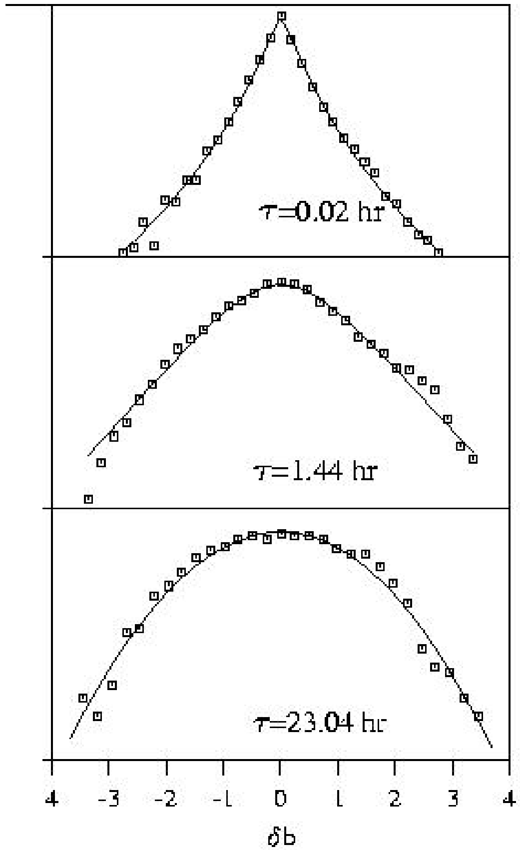
Intermittency along the velocity profile



Analyzing long time intervals is equivalent to mix together solar wind samples intrinsically different

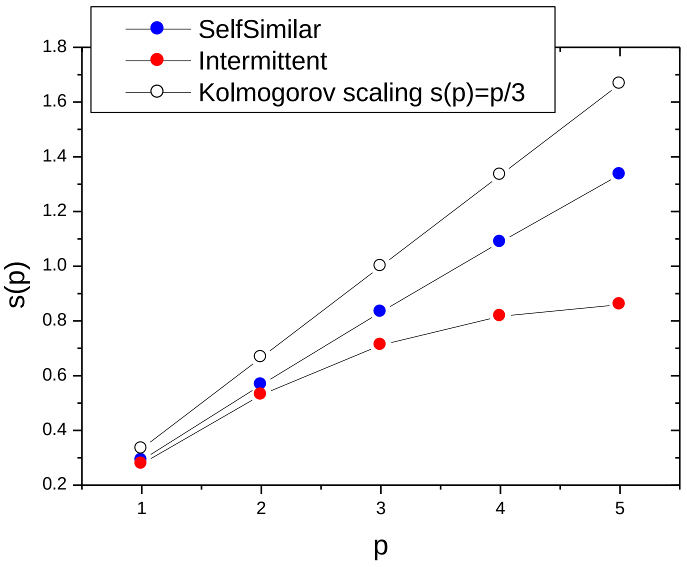


Effect of intermittency on PDFs



This reflects on the non linear behavior of the scaling exponent s(p)

$$S_\tau^p = <|v(t+\tau) - v(t)|^p> \sim \tau^{s(p)}$$



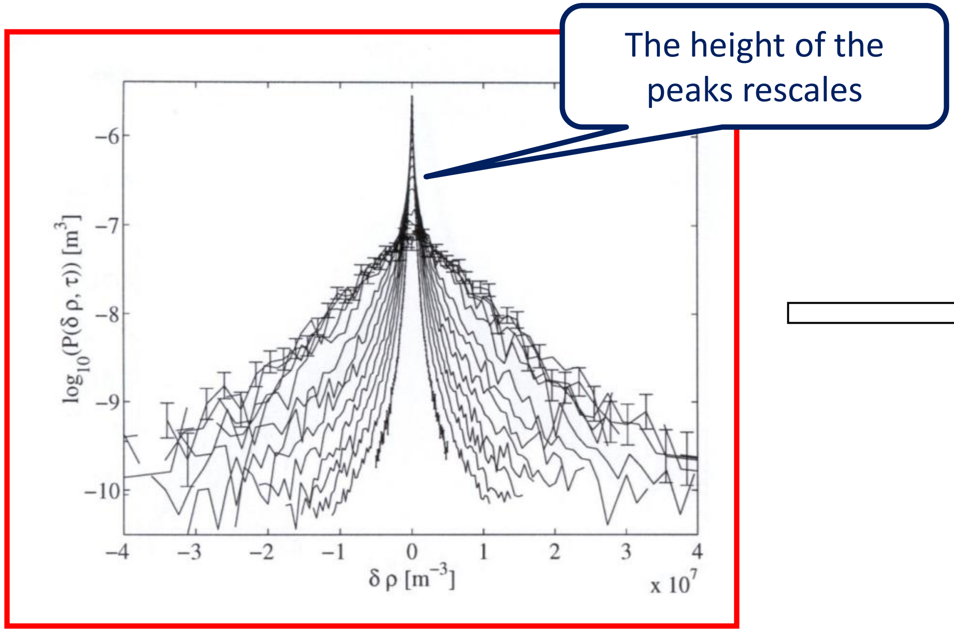
PDF's of δv and δb do not rescale

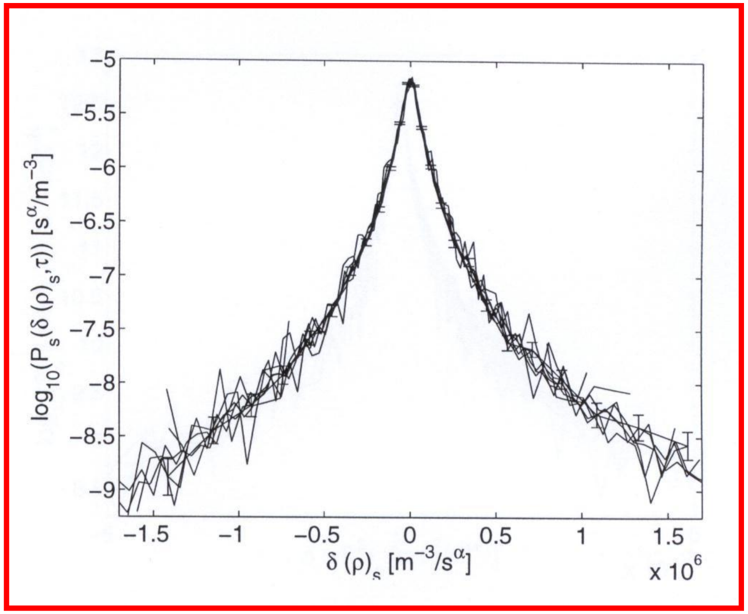
PDFs of other parameters can be rescaled

The PDF of $\delta\rho$, δB^2, $\delta\rho V^2$, $\delta V B^2$ can be rescaled under the following change of variable

$$P(\delta x,\tau) = \tau^{-\alpha} P_s(\delta x \tau^{-\alpha},\tau)$$

(Hnat et al., 2002, 2003, 2004)



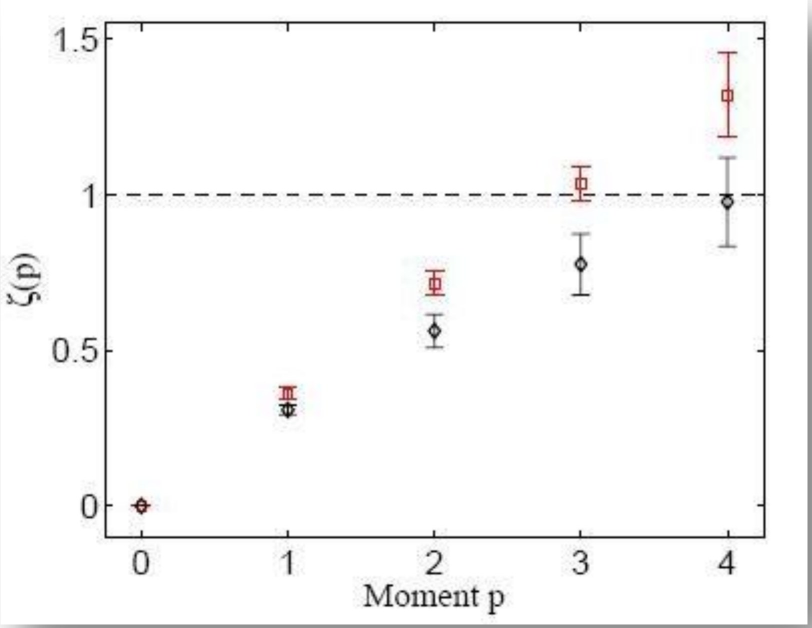


This study showed that:

- the distribution is non Gaussian but it is stable and symmetric and can be described by a single parameter → monofractal
- The process can be described by a finite range Lévy walk (scales up to 26 hours)
- A Fokker-Planck approach can be used to study the dynamics of PDF(δb^2)

Intermittency $\Rightarrow$ anomalous scaling

Studying the anomalous scaling of the different moments can unravel the two components nature of solar wind fluctuations (propagating fluctuations vs advected structures)



(Chapman et al., 2008)

$$\delta v_{//} = \delta \mathbf{v} \cdot \hat{\mathbf{b}}$$

(for Alfvénic fluctuations the scalar product vanishes)

$$\delta v_{\perp} = \left(\delta \mathbf{v} \cdot \delta \mathbf{v} - (\delta \mathbf{v} \cdot \hat{\mathbf{b}})\right)$$

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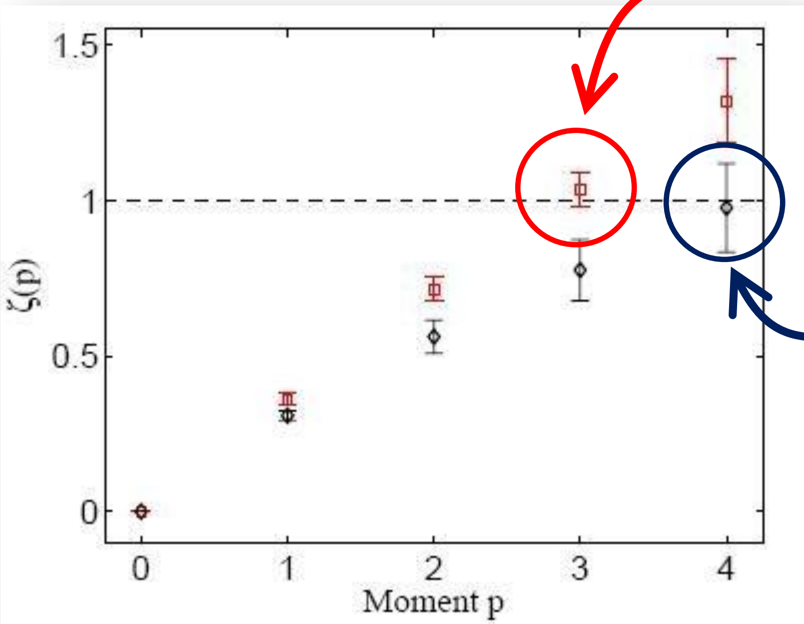
(propagating fluctuations vs advected structures)

Kolmogorov like scaling



(Chapman et al., 2008)

$$\delta v_{//} = \delta \mathbf{v} \cdot \hat{\mathbf{b}}$$

(for Alfvénic fluctuations the scalar product vanishes)

$$\delta v_{\perp} = \left(\delta \mathbf{v} \cdot \delta \mathbf{v} - (\delta \mathbf{v} \cdot \hat{\mathbf{b}})\right)$$

Kraichnan like scaling

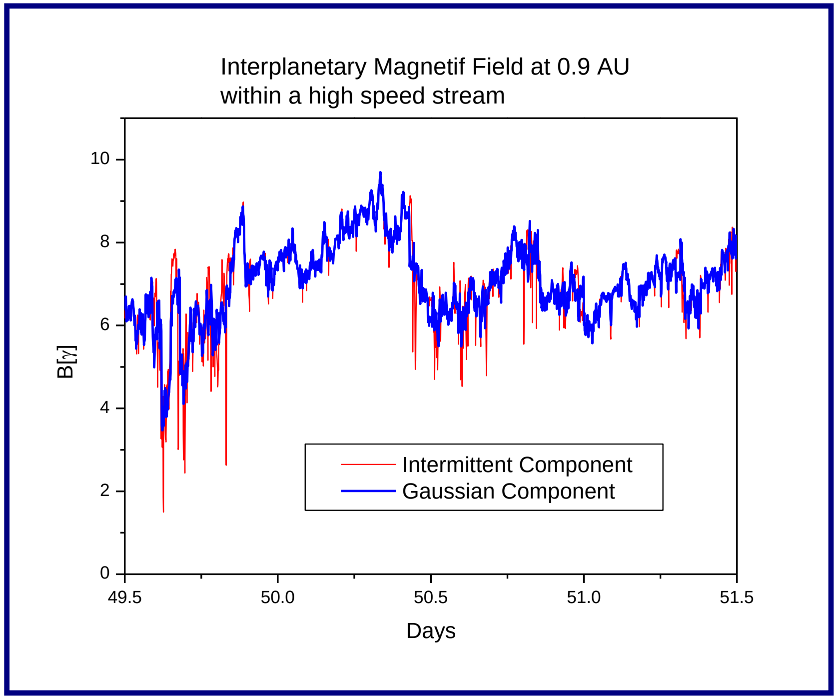
Two possibilities:

1) both components are locally generated by turbulence in the presence of a background field
2) $\delta v_{//}$ is a signature of the base of the corona

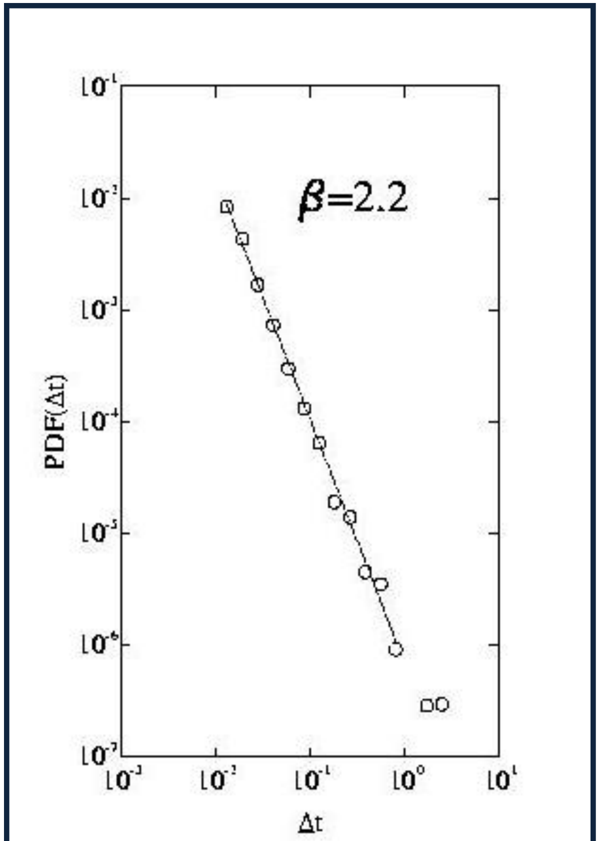
$\delta v_{//}$ quasi self-affine scaling
$\delta v_{\perp}$ multifractal scaling

Two components invoked also by Bruno et al. (2001):

1) Alfvénic component rather <u>Gaussian</u>
2) Advected structures highly intermittent



Results obtained using LIM technique



(Bruno and Carbone, 2005)

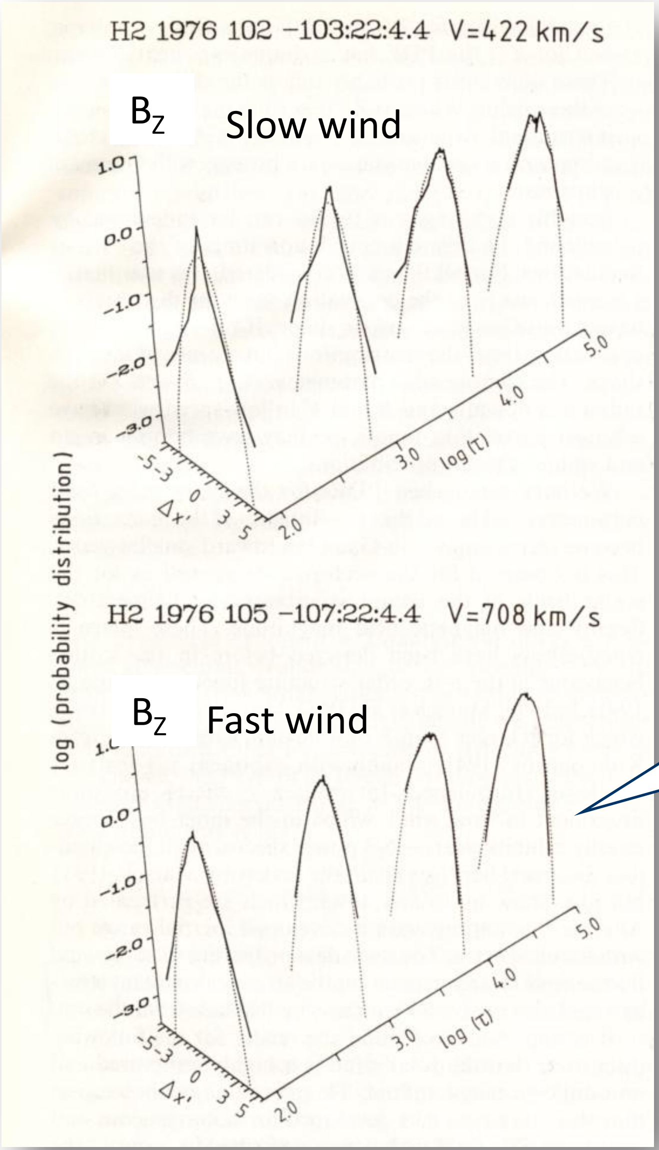
The waiting times are distributed according to a power law $PDF(\Delta t) \sim \Delta t^{-\beta} \Rightarrow$ <u>long range correlations</u>

Thus, the generating process is not Poissonian.

Slow and Fast wind distributions

Stretched

Gaussian

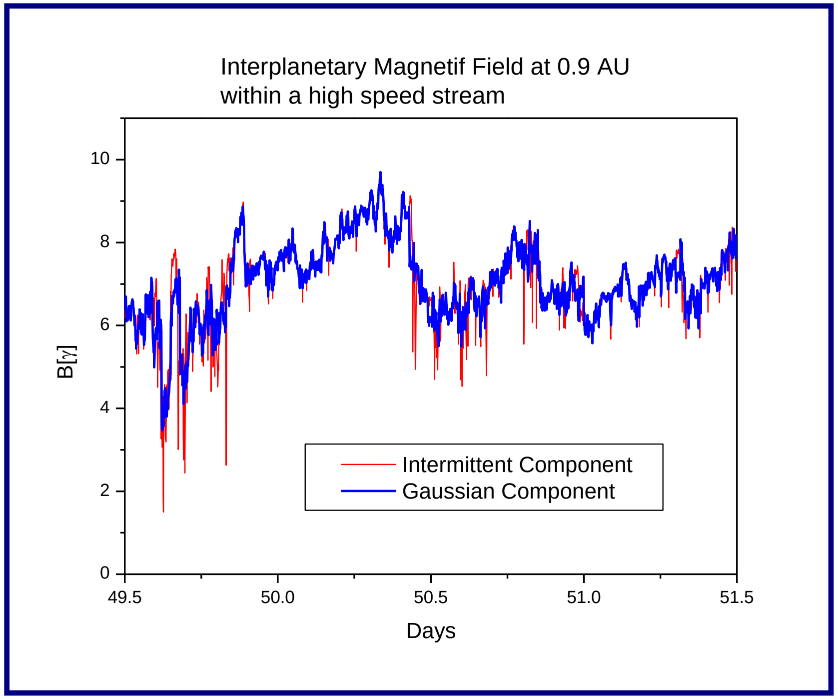


(Marsch and Tu, 1994)

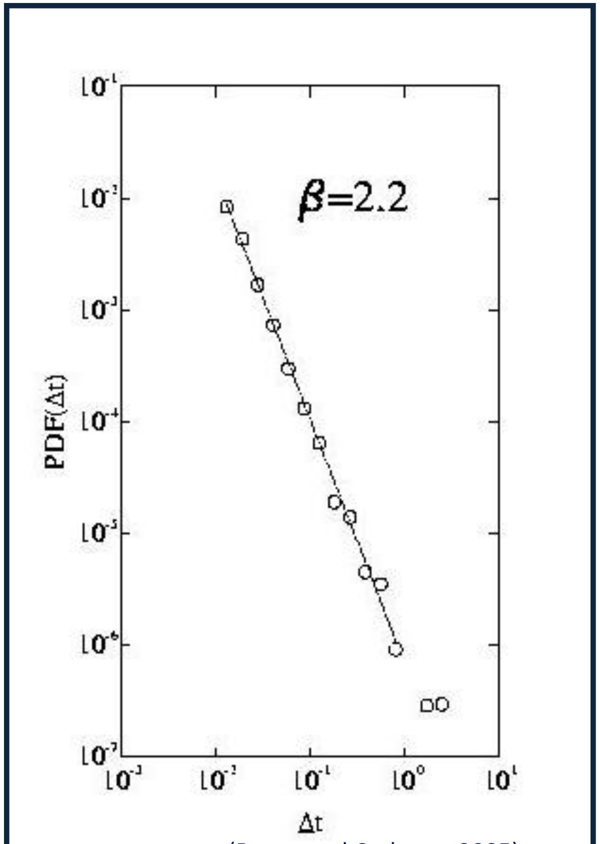
In high speed solar wind, <u>perpendicular components</u> are dominated by stochastic Alfvénic fluctuations and the PDFs are nearly Gaussian

Two components invoked also by Bruno et al. (2001):

1) Alfvénic component rather Gaussian
2) Advected structures highly intermittent



Results obtained using LIM technique



(Bruno and Carbone, 2005)

The waiting times are distributed according to a power law $PDF(\Delta t) \sim \Delta t^{-\beta}$ ⇒ long range correlations

Thus, the generating process is not Poissonian.

Looking at the nature of intermittent events

To measure *Intermittency* we adopt the ***L****ocal* ***I****ntermittency* ***M****easure* (Farge et al[1]., 1990) technique based on wavelet transform

$$< LIM^2(\tau, t) >_t = \frac{< w_{\tau,t}^4 >_t}{< \left| w_{\tau,t} \right|^2 >_t^2}$$

[2]Meneveau (1991) showed that the Flatness Factor of the wavelet coefficients at a given scale τ is equivalent to the Flatness Factor *FF* of data at the same scale τ

$$< LIM^2(\tau, t) >_t = \frac{< w_{\tau,t}^4 >_t}{< \left| w_{\tau,t} \right|^2 >_t^2} \equiv FF(\tau)$$

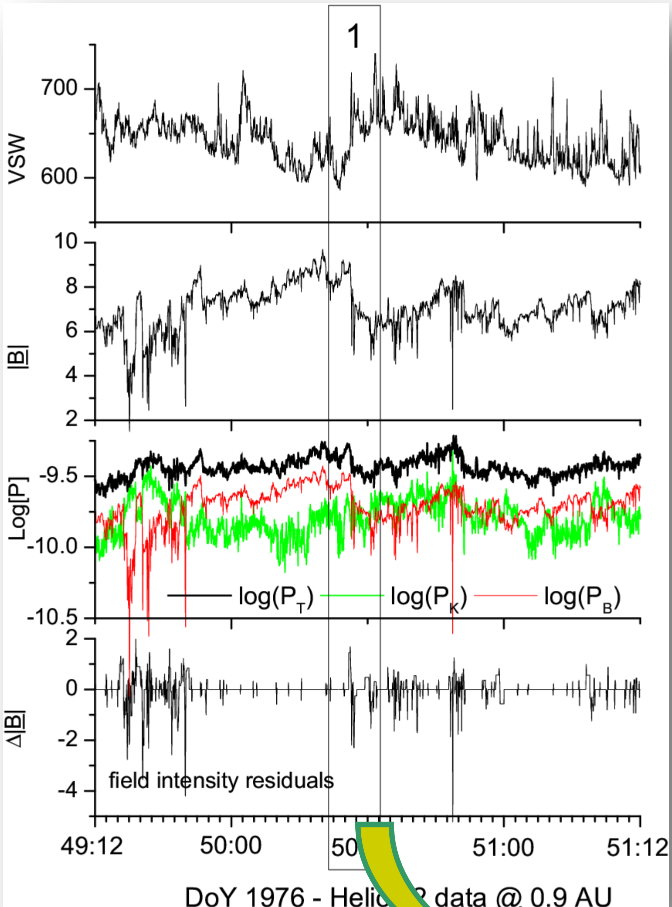
Thus, values of $FF(\tau)>3$ allow to localize events which lie outside the Gaussian statistics and cause *Intermittency*.

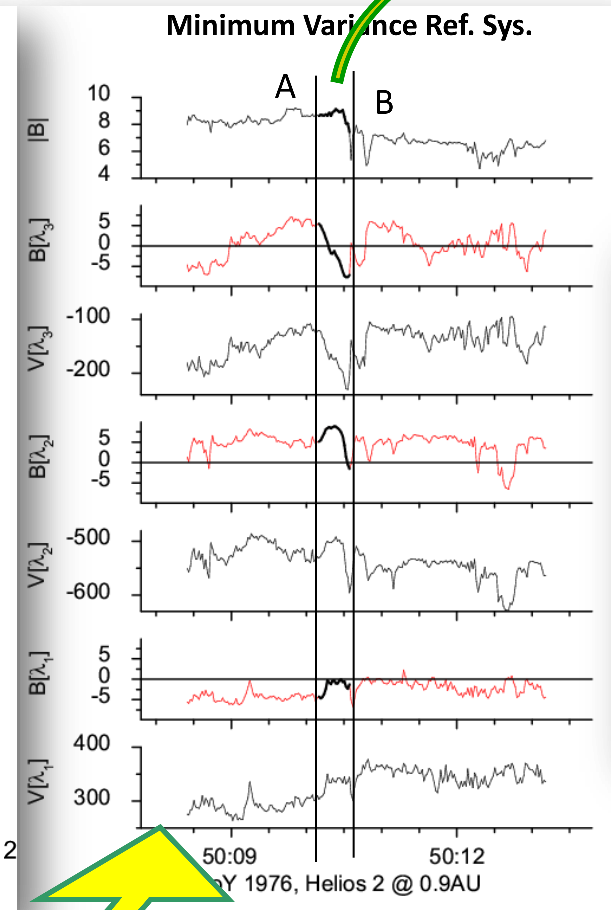
1) In *Topological Fluid Mechanics*, ed H.L.Moffat, Cambridge Univ. Press, 765, 1990
2) Menevau, C., J. Fluid Mech., 232, 469, 1991

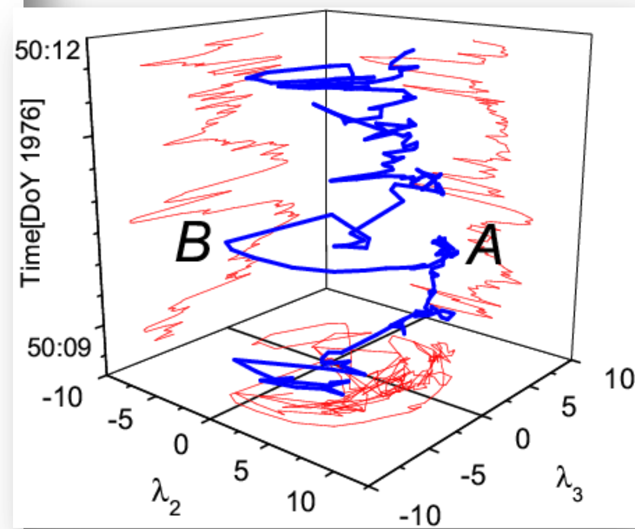
Focusing on a magnetic field intermittent event

Using the Local Intermittency Measure

(Farge, 1990)







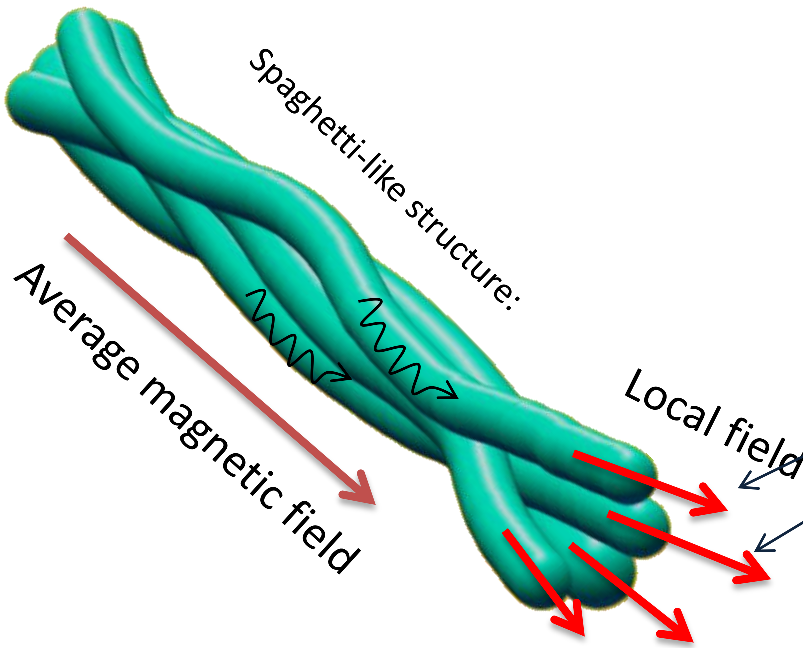
[Bruno et al., 2001]

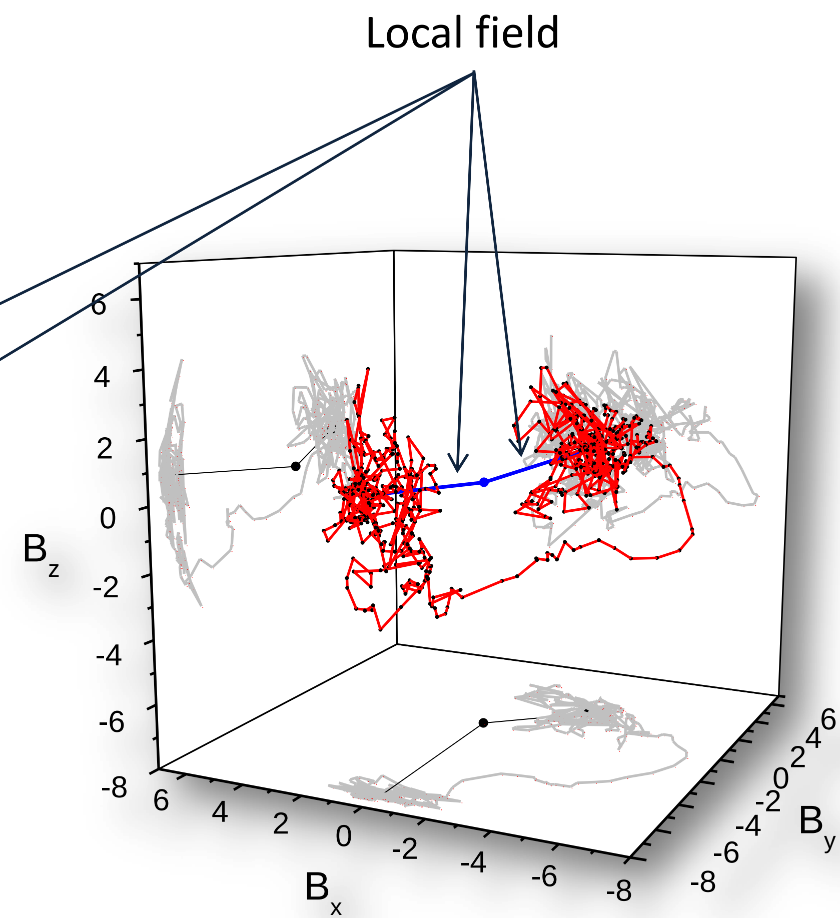
Fluctuations are Alfvénic on both sides of the discontinuity

- the discontinuity is 2-D (Ho et al., 1995)
- there is no mass-flux across it
- it looks like a TD, possibly the border between adjacent flux tubes

These large rotations were identified as the border between adjacent flux-tubes

(Bruno et al., 2001)



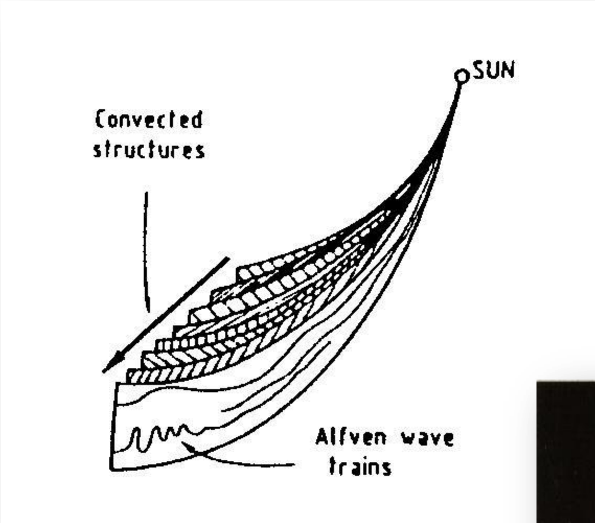


Helios 2, 6sec, 49.628-49.674 (~66min)

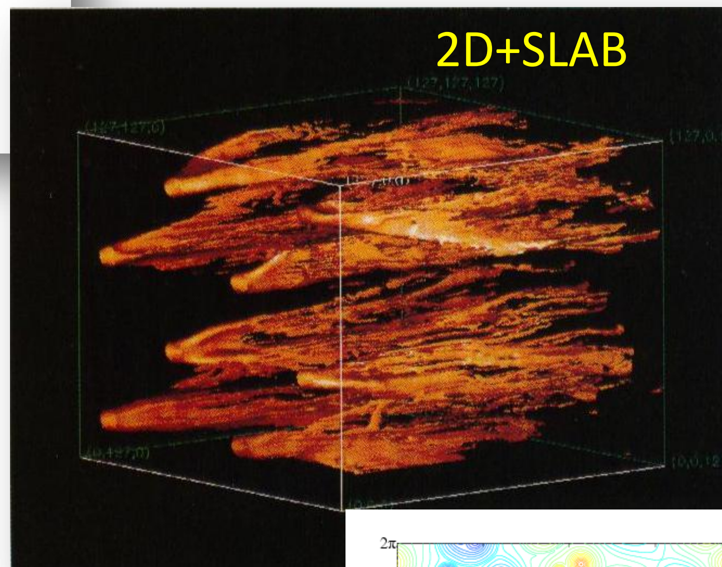
Alfvénic fluctuations would cluster within adjacent flux-tubes along the local magnetic field direction

Several contribution have been given in this direction in the past years

(*Mariani et al.*, 1973; *Thieme et al.*, 1988, 1989; *Tu et al.*, 1989, 1997; *Tu and Marsch,* 1990, 1993; *Bieber and Matthaeus, 1996; Crooker et al.,* 1996; *Bruno et al.*, 2001, 2003, 2004; Chang and Wu, 2002; Chang, 2003; Chang et al., 2004; Tu and Marsch, 1992, Chang et al., 2002, Borovsky, 2006, 2009, Li, 2007, 2008)



[Tu and Marsch, 1992]



[Bieber, Wanner and Matthaeus, 1996]

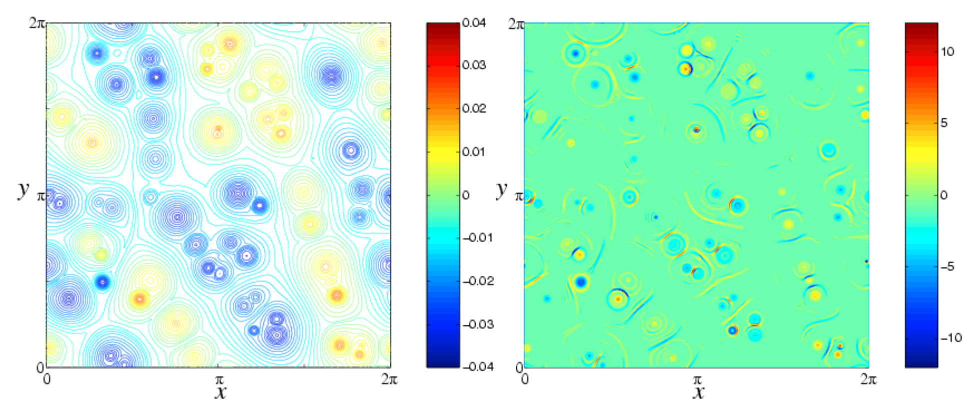


Figure 2.2 2D MHD simulation of coherent structures (left panel) and current sheets (right panel) generated by initially randomly distributed current filaments after an elapsed time of $t = 300$ units. (For reference, the sound wave and Alfvén wave traveling times through a distance of 2π are approximately 4.4 and 60, respectively.)

(Chang et al., 2002)

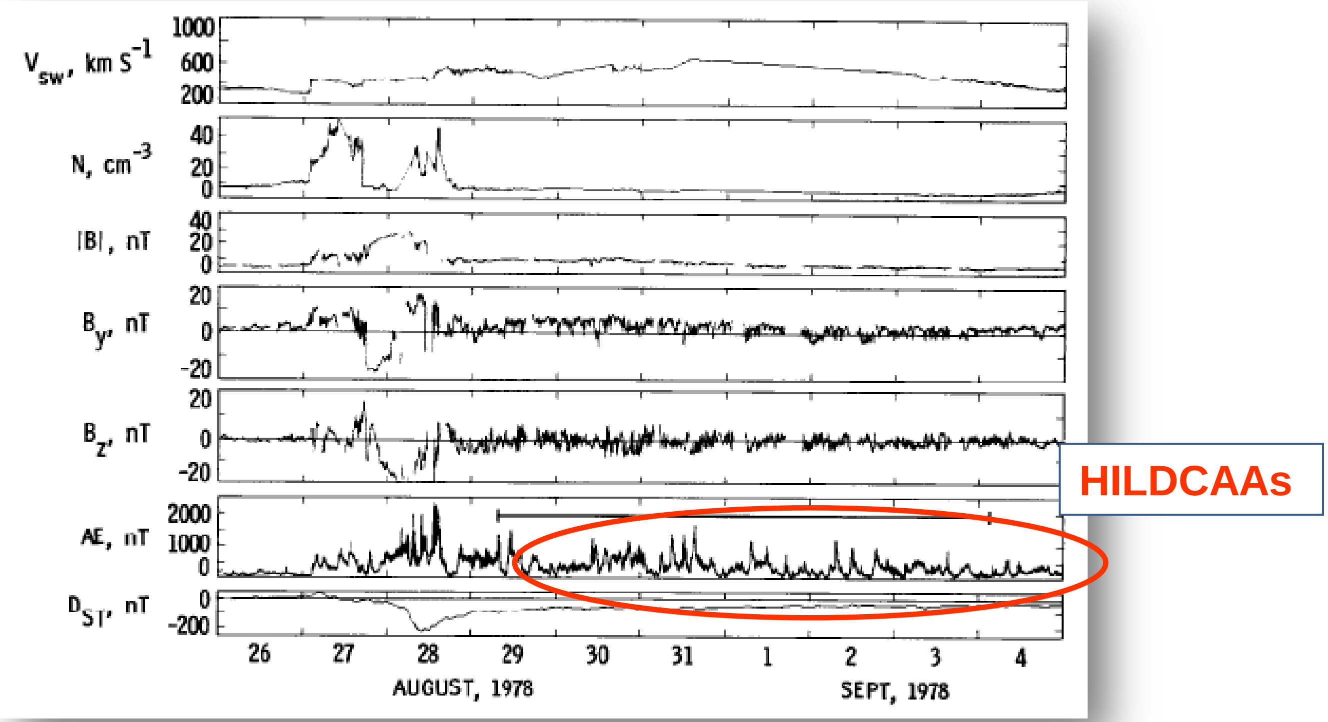
Summary #1

- Experimental estimate of the Reynold's number in the solar wind provide a value of $\sim 3 \cdot 10^5$ at 1 AU
- Turbulence is mainly a mixture of random propagating fluctuations (Alfvénic) and coherent structures (magnetic excess) advected by the wind
- At low frequency, these magnetic structures are responsible for anomalous scaling (intermittency) of fluctuations and emerge from the Alfvénic background as the wind expands
- These structures might have:
    1. either a solar origin, intimately connected to the topology of the source regions at the sun
    2. or a local (interplanetary) origin due to the non-linear dynamics of the fluctuations (turbulence evolution)

Is there any link between turbulence in the solar wind and geomagnetic activity?

Among others, see: Tsurutani and Gonzalez, 1987, Freeman et al. 2000a,b, Hnat et al. 2002, 2003, 2005, Vörös et al., 2002, D'Amicis et al., 2004, 2007

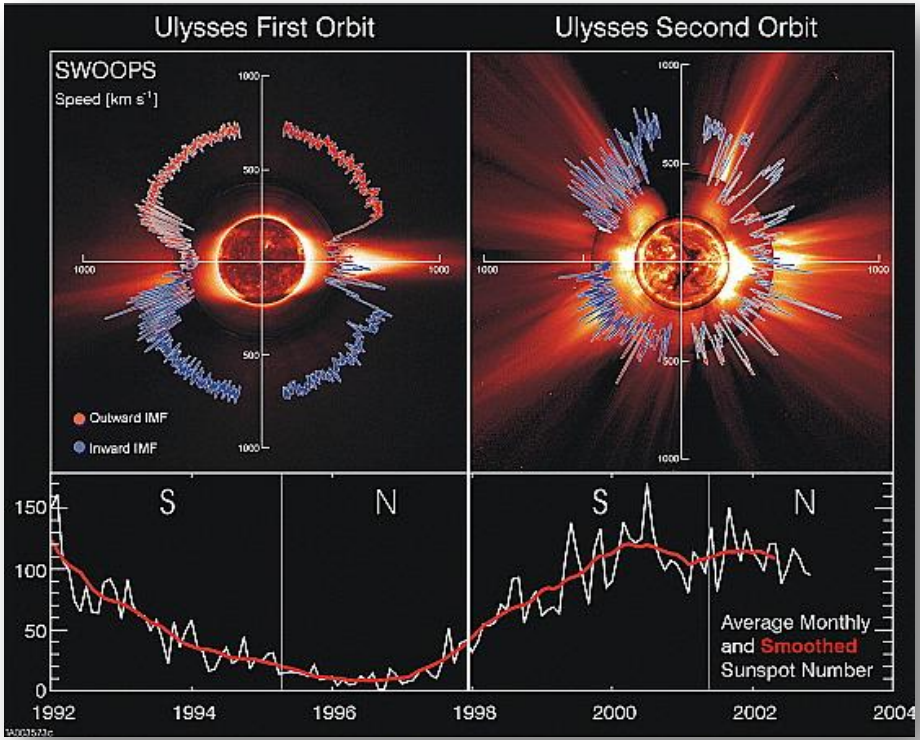
Tsurutani and Gonzalez, 1987 suggested that large amplitude interplanetary Alfvén wave trains might cause intense auroral activities, as a result of the magnetic reconnection between the southward magnetic field z component and the magnetopause magnetic fields.



This suggestion has been tested on statistical basis for different phases of the solar cycle (D'Amicis et al., 2007)

Solar wind large scale structure

Solar minimum:
fast wind at high latitudes and an alternation of slow and fast streams is observed in the ecliptic.

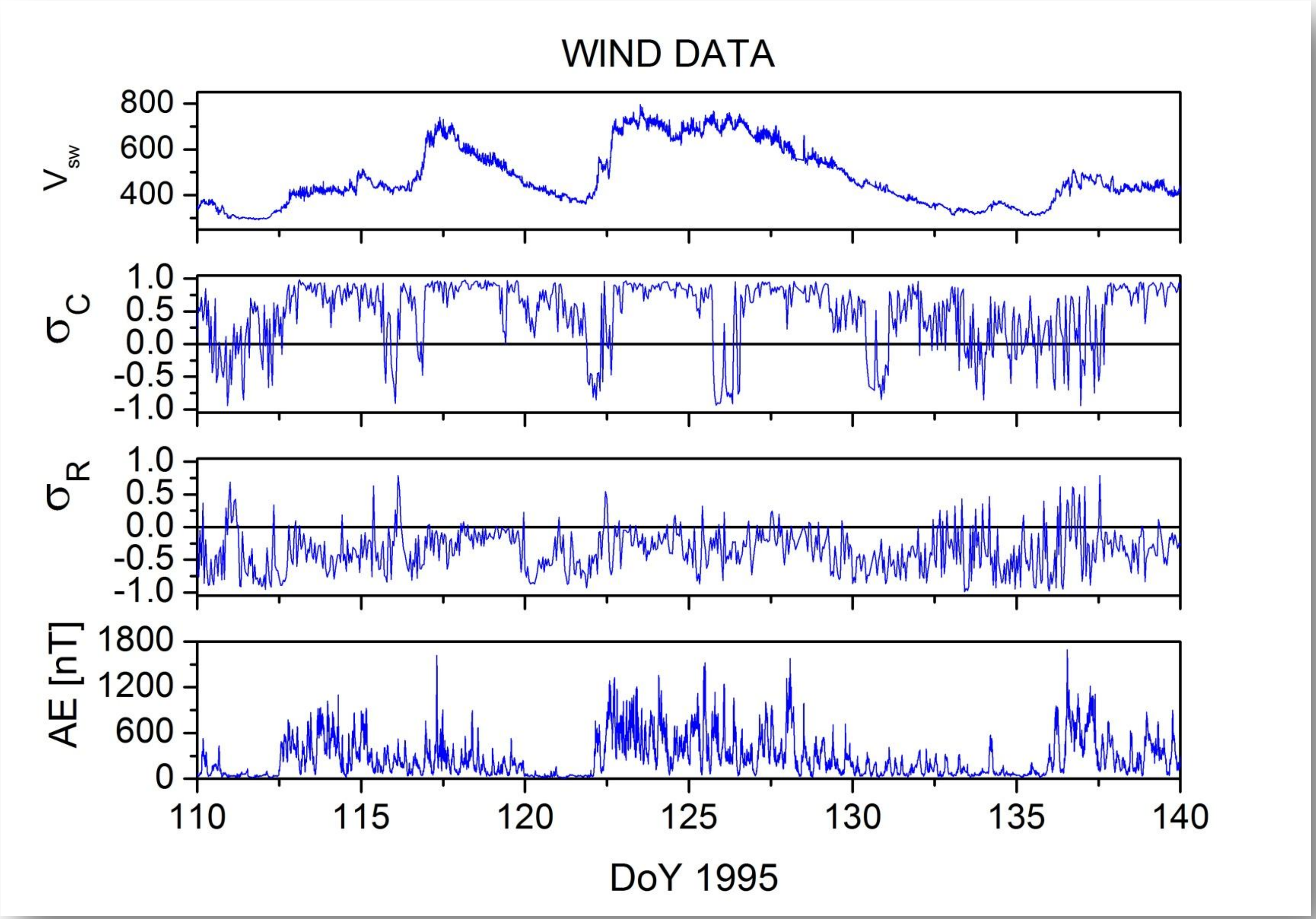


McComas et al, GRL, 2003

Solar maximum:
predominance of slow wind is observed in the ecliptic.

The character of turbulence is different for different phases of the solar cycle because of the different mixture of fast and slow wind

Geomagnetic response vs wind speed, i.e. vs different kind of turbulence

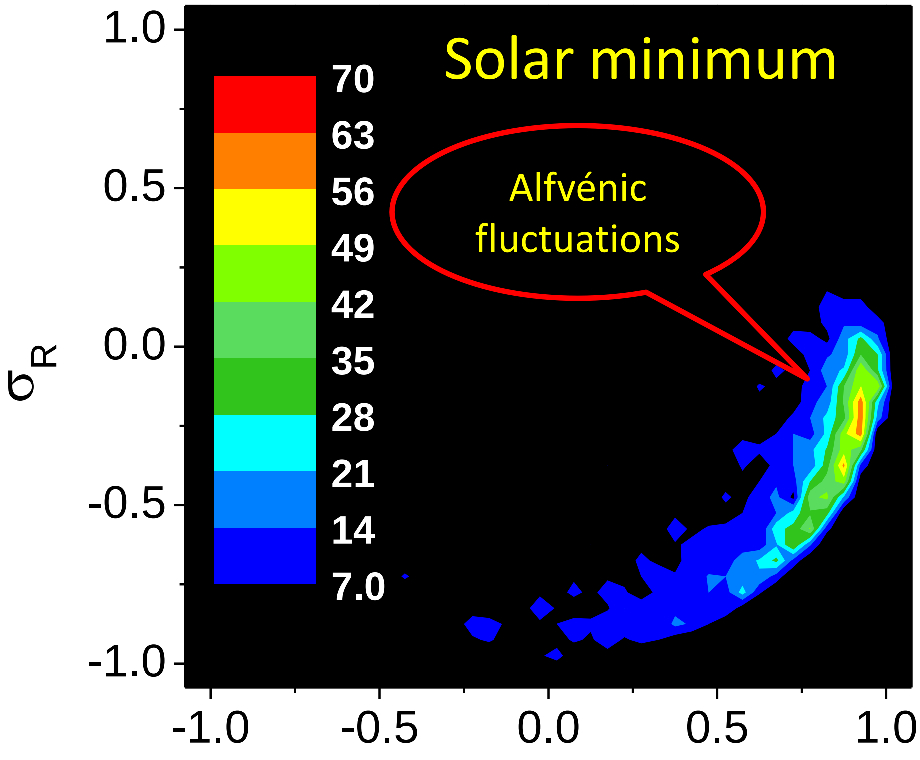


D'Amicis et al., 2007 computed average values of AE in correspondence of every square bin $\Delta\sigma_C$-$\Delta\sigma_R$ at time scale of 1 hour during max and min of solar cycle.

$\sigma_C - \sigma_R$ distributions in the solar wind

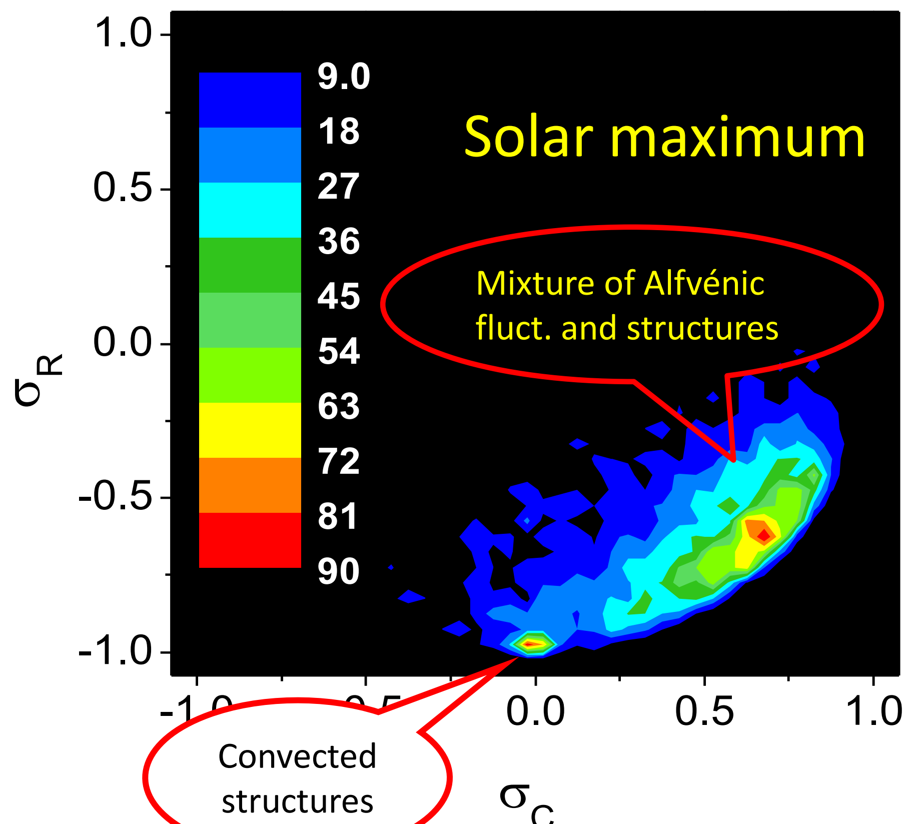
$$\sigma_C = \frac{e^+ - e^-}{e^+ + e^-}$$

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}$$



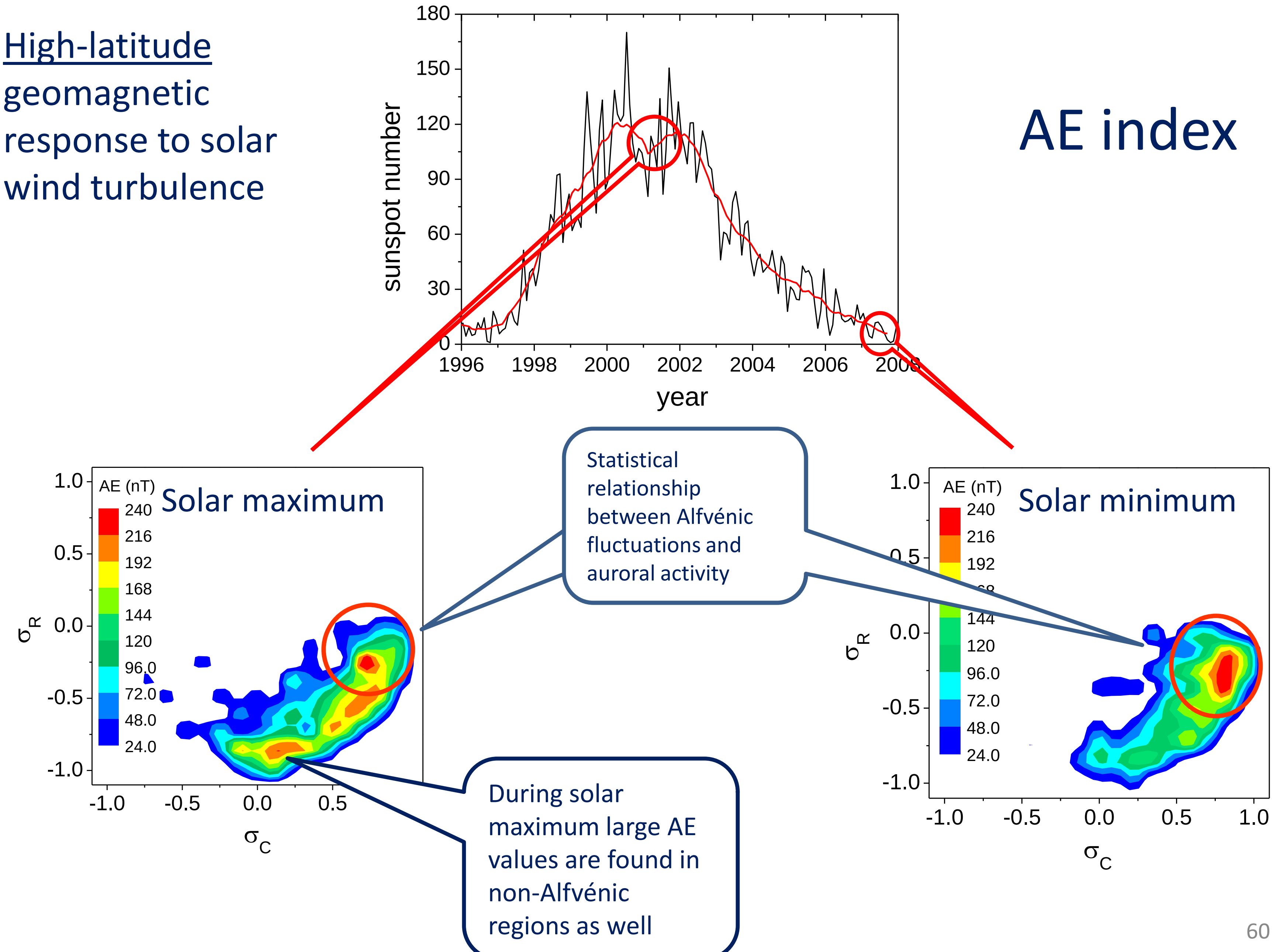
(D'Amicis et al, GRL, 2007)

- Predominance of Alfvénic fluctuations propagating away from the Sun
- Tail elongated towards fluctuations magnetically dominated



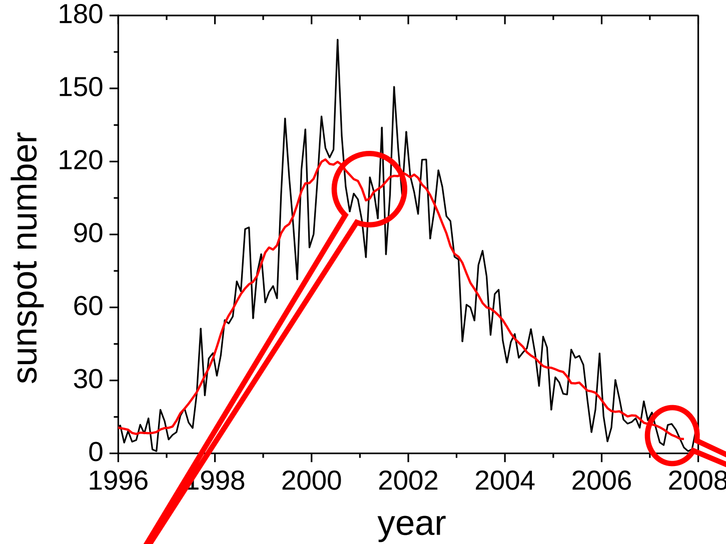
High-latitude geomagnetic response to solar wind turbulence

AE index

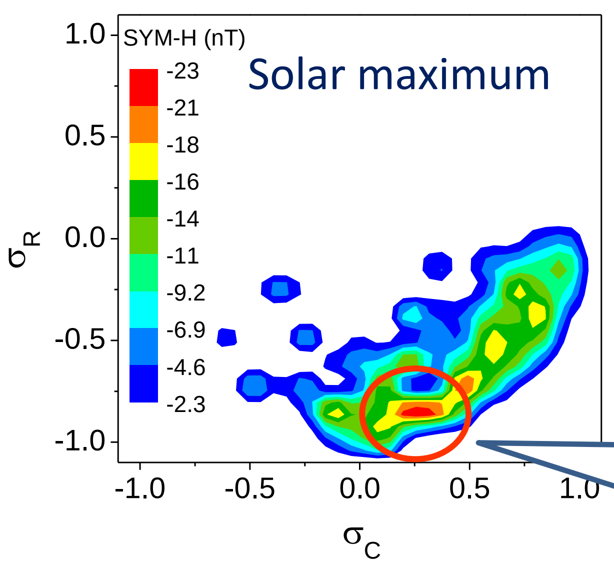


Low-latitude geomagnetic response to solar wind turbulence

SYM- H index



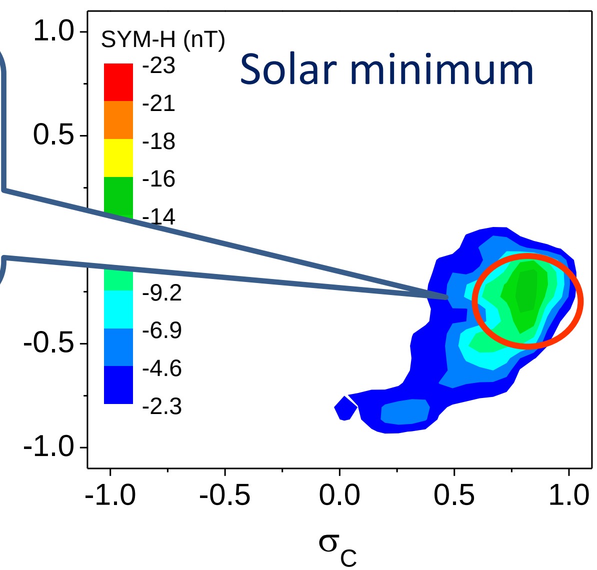
(Wanliss, 2007 suggests that in future studies the SYM-H index be used as a de facto high-resolution Dst index.)



(*D'Amicis et al, 2010*)

Advected structures more effective on SYM-H

Alfvénic fluctuations not very effective on SYM-H



Summary # 2

Low frequency MHD turbulence (inertial range) seems to be geo-effective in driving the solar wind-magnetosphere coupling:

1. Alfvénic turbulence plays a role in driving high latitude geomagnetic activity
2. Advected structures play a role in driving low latitude geomagnetic activity